A Spatial Analysis of Green Technological Innovation and Environmental Sustainability: Exploring the Role of Globalization

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Abstract

The current study investigates the spatial spillover effect of green technological innovations (GI) on environmental sustainability in the presence of globalization (GB). Environmental sustainability is measured using an index called Environmental Health (EH), which reflects environmental quality based on four indicators: air quality, sanitation, heavy metals, and waste management. The study employs spatial methods to analyze the direct, indirect, and total effects of green technological innovation (GI) and globalization (GB) on environmental sustainability across 60 global economies from 1990 to 2022. To investigate the moderating role of globalization (GB), fixed- and random-effects models, structural equation models, and spatial econometric models are estimated. The results show that globalization (GB) has dual moderating effects: while it directly and indirectly (spatially) aggravates environmental pressures, its interaction with green technological innovations (GI) improves environmental sustainability. Similarly, economic development (ED) is found to increase environmental degradation, while urbanization (UR) shows adverse direct spillover effects but improves environmental sustainability at the global scale. The study provides significant policy insights, highlighting the need to understand the repercussions of globalization (GB) and to invest in green technological innovations (GI) to foster a sustainable global environment.

Keywords: Green Technological Innovation, Environmental Sustainability, Ecological Footprint Per Capita, Biocapacity Per Capita, Spatial Econometric Analysis.

Introduction

In the globalized era, urbanization and industrialization have intensified pressures on natural ecosystems, pushing the planet closer towards its ecological limits. It contributes to rising global temperatures and accelerates climate change. The past decade has been the warmest on Record, and forecasts indicate that global surface temperatures may increase by 1.4 to 8°C over the next century, posing serious threats to biodiversity and ecological systems. These problems will create challenges for environmental sustainability and the capacity of green technological innovations to ease environmental degradation.

Studies show that most countries remain dependent on non-green technologies and resource-intensive production structures, reinforcing carbon-intensive growth patterns (Sun et al., 2022). While environmentally friendly technologies help reduce environmental degradation (Chen, 2008; Lin & Ho, 2008; Lee & Kim, 2011; Wang et al., 2019; Dabbous & Barakat, 2023). Although technological development also offers opportunities for cleaner production and

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improved resource efficiency, the pursuit of economic growth often continues to outweigh ecological considerations, thereby undermining environmental health. Besides, the efficiency of green technological innovations is constrained by insufficient policy frameworks, information failures, and poor institutional frameworks, particularly at the global scale (OECD, 2011). In this backdrop, empirical evidence on the effectiveness of green technological innovations across countries in advancing environmental sustainability remains highly debatable. Hence, the need for an environmentally sustainable technological framework has long been recognized in the literature.

Meanwhile, globalization has inflated economic integration, capital mobility, trade flows, and technological interactions across countries. Its environmental consequences, however, remain unclear. On the one hand, globalization increases ecological pressures by boosting production and consumption, thereby expanding ecological footprints and worsening environmental degradation (You & Lv, 2018; Kirikkaleli et al., 2021). On the other hand, globalization promotes efficiency gains, knowledge spillovers, and technological diffusion, possibly supporting environmental sustainability under suitable institutional and regulatory setups (Ahmad et al., 2022). These conflicting effects suggest that globalization can moderate the effects of green technological innovation on environmental sustainability, warranting further empirical investigation.

While investigating environmental sustainability, the traditional indicators such as greenhouse gas emissions, CO_2 emissions, ecological footprints, and the load capacity factor are widely used (Wang & Zhu, 2020; Chen & Lee, 2020; Gani, 2021; Han et al., 2021; Wu et al., 2021; Siche et al., 2010; Aydin & Degirmenci, 2024). While these measures mainly ignore some important players in climate change, such as air quality, sanitation and drinking water, heavy metals, and waste management. In addition, the role of spatial interdependence, cross-border spillovers, and feedback mechanisms remains insufficiently explored, despite the interconnected nature of global economies. Also, the environmental effects of green technological innovations may differ across different stages of economic development and income levels, indicating potential nonlinear and threshold dynamics (Aneja, Yadav & Gupta).

Against this backdrop, the present study investigates the spatial effects of green technological innovation on environmental sustainability while clearly examining the moderating role of globalization. Identifying spatial interdependence among economies, the study employs spatial econometric methods to analyze the spatial decomposition of effects (direct and indirect). Using a set of 60 global economies spanning 1990 to 2022, the study incorporates fixed- and random-effects models, panel structural equation modeling, and the Spatial Durbin Model to investigate local and global interactions. By addressing spatial spillovers and cross-country heterogeneities, the study contributes to the existing empirical literature on how green technological innovations and globalization together affect environmental sustainability outcomes. In doing so, it offers significant policy implications for aligning globalization policies with investments in green technologies to foster a sustainable environment.

The study is organized as follows: Section 2 is the literature review. Section 3 explains the methodology and data. Section 4 presents the empirical findings, results, and discussions. Section 5 concludes the whole study with the key findings and policy recommendations.

Literature Review

Green Technological Innovation and Environmental Sustainability

The relationship between green technological innovations and environmental sustainability is rooted in Schumpeter's (1942) concept of creative destruction, which emphasizes technological progress as a driver of long-term development. Building on this foundation, green technological innovation has emerged as a critical mechanism for achieving environmental sustainability by reducing pollution, improving resource efficiency, and supporting sustainable production systems (Chen et al., 2012; Yang et al., 2016). A growing body of empirical literature documents the environmental benefits of green innovation across firm, sectoral, and national levels. Early firm-level studies show that green innovation enhances environmental performance, lowers emissions, and improves efficiency (Lin & Ho, 2008; Chen, 2008; Tseng et al., 2013a). Subsequent research highlights the role of institutional support, R&D, human capital, and knowledge management in driving green innovation and sustainability outcomes (Cuerva et al., 2014; Abbas & Sagsan, 2019). Green and eco-innovations, often used interchangeably, are consistently found to support sustainability by mitigating environmental hazards and improving firms' competitive advantage (Castellacci & Lie, 2017; Chu et al., 2019; Fernando & Wah, 2017).

At the macro level, numerous studies confirm that green technological innovation reduces environmental degradation and ecological pressure, particularly through green patents and the adoption of clean energy (Alvarez-Herranz et al., 2017; Long et al., 2017; Banday & Aneja, 2019; Adebayo & Kirikkaleli, 2021). However, recent evidence also points to heterogeneity and non-linear effects, with environmental gains varying by income level, institutional quality, and technological efficiency (Töbelmann & Wendler, 2020). More recent studies adopt advanced econometric and spatial approaches to capture these complexities. Spatial analyses reveal that green innovation generates both domestic and cross-border spillovers, though their magnitude depends on regional proximity, human capital, and governance quality (Huang, 2021; Radmehr et al., 2023). Clean energy and green innovation have been shown to improve environmental sustainability in the EU, G20, BRICS, and G7 economies, although results differ across quantiles, time horizons, and development stages (Naqvi et al., 2025; Feng et al., 2024; Ozkan et al., 2024).

The most recent literature further integrates globalization, FDI, finance, and institutional quality into the green innovation–environment nexus. While green technologies and renewable energy generally enhance sustainability, globalization, economic complexity, and financial integration may exert adverse effects unless aligned with environmental objectives (Wani et al., 2024; Sethi et al., 2024). Overall, the literature indicates that green innovation is a key, yet context-dependent, driver of environmental sustainability, with its effectiveness shaped by non-linearities, spatial spillovers, and interactions with globalization and institutional structures.

Globalization and Environmental Sustainability

The relationship between globalization, innovation, and the environment is a prominent topic in economic research. Numerous studies have investigated the connections between globalization and the environment. Globalization typically involves increased trade and investment flows (Dreher, 2006), greater emphasis on research and development (Murray et al., 2016), and expanded networks at the country and regional levels (Gygli et al., 2019). The extent to which the benefits of globalization, such as technological progress, translate into tangible outcomes depends on the level of technological spillover, which is influenced by the capacity for innovation at various levels (Ebersberger & Herstad, 2013).

Shahbaz et al. (2017b) have explored the globalization-environment nexus for Japan for the period of 1970 to 2014. The findings show that the growth of globalization and the increasing demand for non-renewable resources are creating a significant environmental challenge. In the same context, Haseeb et al. (2018) tested the EKC hypothesis to examine the relationships among environmental performance, globalization, economic growth, energy consumption, financial sector performance, and urban growth in five highly populated countries: India, China, Russia, Brazil, and South Africa. The results show that CO_2 declines meaningfully with increasing globalization.

- Some recent empirical insights include Sun et al. (2021), who explore the asymmetric impact of green innovation, globalization, and economic growth on CO2 emissions using data from the world's top 10 most polluted economies for the period 1991 to 2018. The authors concluded that globalization increases carbon emissions, while green innovations significantly reduce them. However, Ahmad and Wu (2022) argued that globalization and innovations together have a positive impact on environmental sustainability.
- The literature shows that globalization plays a dual role in determining environmental sustainability, highlighting both its positive and negative impacts. Rasool, Jianguo, and Ali (2024) studied how globalization impacts emissions in Indonesia from 1990 to 2020. The results showed that economic globalization enhances emissions, while social globalization alleviates environmental degradation. On the other hand, there is no significant impact of political globalization on CO2 emissions. Moreover, energy use and economic development increase emissions, whereas the EKC showed a reduction in environmental deterioration and an intensification in environmental sustainability. The emissions and ecological footprint consumption are further studied by Ghosh et al. (2024). The results showed that industries with advanced modern technologies positively impact environmental health, while renewable energy and natural resource accumulation mitigate environmental challenges. Girlovan et al. (2025) measured environmental sustainability using globalization (trade openness), greenhouse gas (GHG) emissions, and energy intensity for the 27 EU countries from 2005 to 2022. Overall, the literature suggests that globalization plays a dual, context-dependent role in environmental sustainability, underscoring the importance of innovation, regulation, and complementary policies to translate globalization-driven integration into environmental gains.

a) Spatial Effects of Green Technological Innovations

Environmental issues and technological changes interact in space; they are not independent phenomena, are inherently spatial, correlated across boundaries, and are largely influenced by regional factors, externalities, and regional interactions (Elhorst et al., 2017). Zhang et al. (2024) examined the impact of green technologies on the environmental outcomes of 253 cities in China, using panel data spanning 2010 to 2020. The results reveal that green technological innovations exhibit positive spatial spillover effects, significantly improve environmental outcomes, and reduce CO_2 emissions. Likewise, Liu & Kang (2024), who studied the 30 provinces of China over the period 2000 to 2019, reported a significant negative relationship between green technological innovations and CO_2 emissions. Wang, Cui, & Zhao (2021) found a more complex picture of the relationship between green technological innovations and environmental outcomes of 30 Chinese provinces for the period of 2000 to 2026. While green technological innovation was found to have a positive and significant impact on GTFP locally, confirming its local benefits, the spatial spillover effects remain negative. Some recent studies confirm a spatial positive relationship between green innovation and environmental sustainability locally and in neighboring regions, though spillovers may vary in direction and magnitude (Naqvi et al., 2025).

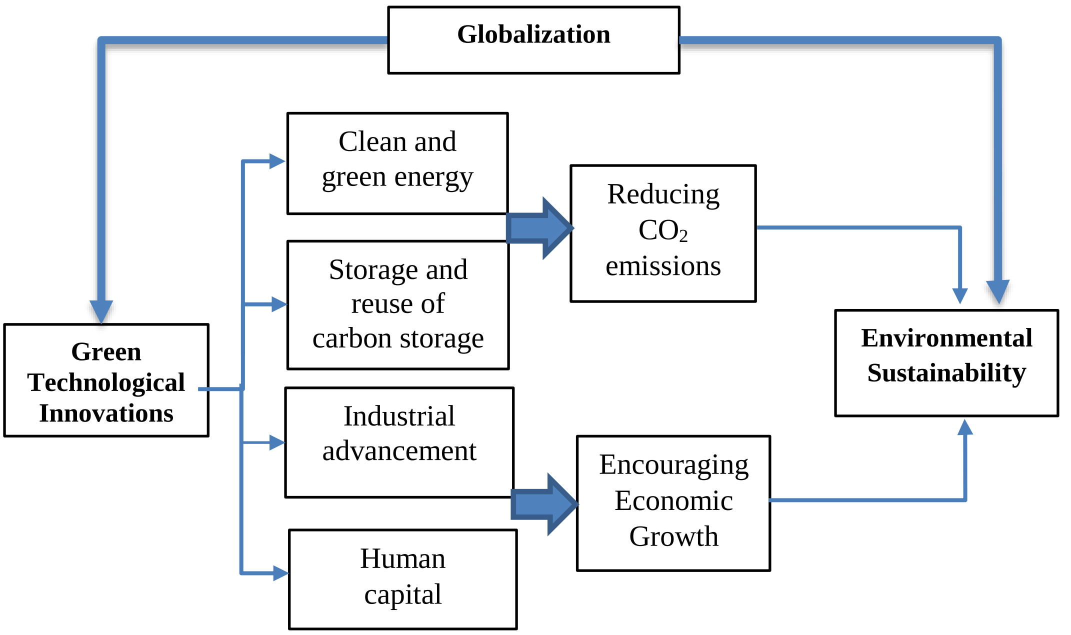
Bai et al. (2024) examined how green technological innovations are themselves shaped by digital innovations across 26 cities in the Yangtze River Delta from 2012 to 2019. Using a spatial econometric framework, the study found that the digital economy significantly enhances local green technological innovation and, in turn, generates positive spatial spillovers to adjacent cities. All of these studies provide strong empirical support for the argument that green technologies and innovations are crucial not only for the environmental sustainability of the implementing countries but also for their neighboring countries. In other words, green innovations have both direct and indirect spatial (spillover) impacts on environmental sustainability. The majority of the studies confirm the existence of positive spatial spillover effects, signifying that green policies can generate regional benefits. However, some conflicting findings, for example, Wang et al. (2021), show negative spatial externalities, underline the complexity of these dynamics and the need to consider interregional competition and policy coordination.

Although the literature on environmental sustainability is extensive, several critical gaps still remain under-explored. First, most studies rely on narrow environmental indicators, such as CO_2 emissions, while overlooking broader sustainability dimensions, as the Environmental Health Index explains. Second, spatial interactions and spillover effects of green innovation are rarely examined at the global level. Third, the moderating role of globalization in shaping the green innovation–environment nexus remains underexplored. This study addresses these gaps by employing a comprehensive environmental indicator called the environmental health index, integrating spatial econometric techniques, examining spatial dynamics, and explicitly modeling globalization as a moderator using a broad global dataset (1990–2022).

Conceptual Framework

Before delving into the detailed empirical analysis, it is important to review the possible channels through which green technological innovations can significantly contribute to environmental sustainability, as depicted in Figure 1.

Figure 1: Flowchart of Green Technological Innovations, Globalization and Environmental Sustainability



Source: Idea taken from Ahmed et al. (2022) and modified by the author with the help of theoretical foundations.

First, green technological innovations improve energy efficiency, promote clean and green energy for production, thus it controls the emissions of hazardous gases. Second, it might deliver some likely alternative means to handle carbon dioxide emissions such as carbon reuse and storage. Third, green innovations promote industrial capacity, from low value-added industries to modern and high value-added industries which in turn push economic growth. Fourth, green innovations also help to advance human capital which is a well-known factor of sustainability. This channel of green technological innovations also shows that it creates an equilibrium between economic growth and sustaining the environment through reducing the emissions of greenhouse gases (Weina et al., 2016).

Research Methodology

The study uses a panel data of 60 economies (middle- and high-income) spanning from 1990 to 2022. The sample confirms sufficient cross-country multiplicity and satisfactory observations for consistent statistical analysis, supporting robust and pertinent empirical inferences. The construction of all the studied variables are discussed in the Table 1.

Table 1: Connotation of Variables

<table>
<tr><th>Description</th><th colspan="3">Construction</th></tr>
<tr><td colspan="4">Environmental Sustainability (dependent variable)</td></tr>
<tr><td rowspan="6">Environmental Health Index (EH_{it})</td><td colspan="3">Environmental Health Index (EH_{it}) is constructed for the sample countries by following the criteria of Environmental Performance Index (EPI) 2020. It is based on four key indicators:</td></tr>
<tr><td>Issue Category</td><td>Weight</td><td>Indicators</td></tr>
<tr><td>i. Air Quality</td><td>50%</td><td>PM2.5 Exposure,
Household Solid Fuels, Ozone Exposure</td></tr>
<tr><td>Sanitation & Drinking Water</td><td>40%</td><td>Unsafe Sanitation and Unsafe Drinking Water)</td></tr>
<tr><td>Heavy Metals</td><td>5%</td><td>Lead Exposure</td></tr>
<tr><td>Waste Management</td><td>5%</td><td>Controlled Solid Waste

Data is extracted from the Institute for Health Metrics and Evaluation, Copernicus, Wolf et al. 2021, Chen et al 2020, and Meijer et al. 2021.</td></tr>
<tr><td colspan="4">Green Technological Innovation (policy variable)</td></tr>
<tr><td>Green Technological Innovations (GI_{it})</td><td colspan="3">GI_{it} refers to inventive activities reflected in patent developments across various environment-related technological fields, including environmental management systems, water adaptation technologies, and climate change mitigation solutions. The measure focuses specifically on higher-quality, high-value patent inventions to capture meaningful technological advancements.
Data is collected from OECD data bank.</td></tr>
<tr><td>Renewable Energy (RE_{it})</td><td colspan="3">RE_{it} is measured as the share of renewable energy in total final energy consumption. It refers to the energy derived from green sources that are renewable, such as solar, wind, hydro, and geothermal power. As a proxy measure of green innovations, renewable energy signifies the advancements in technology that reduce environmental harms, promote sustainability, and contribute positively to towards a cleaner, greener and sustainable future.
Data is collected from WDI data bank.</td></tr>
<tr><td colspan="4">Globalization (moderating variable)</td></tr>
<tr><td>Globalization (GB_{it})</td><td colspan="3">KOF Economic globalization (scale of 1 to 100) covers both trade flows as well as financial flows. De facto trade is determined with reference to the trade in goods and services. De jure trade covers customs duties, taxes and restrictions on trade.
Data is collected from ETH Zurich KOF data bank.</td></tr>
<tr><td colspan="4">Control variables</td></tr>
<tr><td>Urbanization (UR_{it})</td><td colspan="3">Urbanization is measured in the growth rate of urban population.
The data is collected from World Development Indicators (WDI).</td></tr>
<tr><td>Economic Development (ED_{it})</td><td colspan="3">Economic Development is measured as the percentage change in a country’s Gross Domestic Product (GDP) over a specific period, usually measured annually or quarterly.
Data is collected from World Development Indicators (WDI).</td></tr>
</table>

Spatial Weight and Spatial Dependence

For the empirical analysis, inverse distance and k-nearest neighbor spatial weight matrices are employed. In the inverse distance matrix, a cut-off distance of 5 km is applied, and weights are defined as;

$$w_{ij} = \begin{cases} 1, & 0 < d_{ij} < d \\ 0, & d_{ij} > d \end{cases}$$

$$w_{ij} = \begin{cases} 1, & 0 < 5km < d \\ 0, & 5km > d \end{cases}$$

One way to model this is to specify spatial weights in the form of the inverse of the distance between spatial units. Hence, weights are specified as:

$$w_{ij} = d_{ij}^{-\alpha}$$

'α' is normally assumed to be '1' or '2'. In this case, all the spatial units are neighbors to some degree. By following LeSage and Pace (2009), spatial weights matrices ensure the row normalization (sum of row is equal to 1 and diagonals are 0), by adjusting for the varying number of neighbors. In the K-nearest weight matrix approach, we specified the number (K) of neighbors, and then the K-nearest units are identified as neighbors. The "K" are 5 in this study. The distance between the spatial units is measured by specifying the capital city as the spatial unit. Prior to spatial analysis, spatial dependence in the dependent variable is examined using the global Moran's I statistic. Moran's, I range from −1 to +1, where negative (positive) values indicate spatial dispersion (clustering), and a value of zero implies no spatial autocorrelation (Getis & Ord, 1992). Spatial interaction patterns are first identified using Moran's I, computed following Anselin and Getis (1992) and Anselin (1995).

$$Moran's\ I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}(ES_i - \overline{EH})(EH_j - \overline{EH})}{S^2 \sum_{i=1}^{n}\sum_{i=1}^{n} W_{ij}}$$

$$S^2 = \frac{1}{n}\sum_{i=1}^{n}(EH_i - \overline{EH})$$

Where, n shows number of countries, W_{ij} shows spatial weight matrix symbolizing the spatial proximity of country "i" to country "j".

Model Specification

Ignoring spatial effects may lead to biased estimates in conventional econometric models, as environmental and technological processes are spatially interdependent. Spatial econometric models address this issue by incorporating spatial dependence through weight matrices, with the Spatial Durbin Model (SDM) being the most comprehensive as it accounts for spatial lags of both the dependent and explanatory variables (LeSage & Pace, 2009; Elhorst, 2014).

$$\begin{aligned} EH_{it} = {} & \alpha + \rho \sum_{j=1}^{n} W_{ij}EH_{it} + \beta_1 GI_{it} + \beta_2 GI_{it}^2 + \beta_3 ED_{it} + \beta_4 UR_{it} + \beta_5 GB_{it} \\ & + \beta_6 (GI * GB)_{it} \\ & + \theta_1 \sum_{j=1}^{n} W_{ij}GI_{jt} + \theta_2 \sum_{j=1}^{n} W_{ij}GI_{it}^2 + \theta_3 \sum_{j=1}^{n} W_{ij}ED_{jt} \\ & + \theta_4 \sum_{j=1}^{n} W_{ij}UR_{jt} + \theta_5 \sum_{j=1}^{n} W_{ij}GB_{jt} + \theta_6 \sum_{j=1}^{n} W_{ij}(GI * GB)_{jt} + c_i \\ & + \mu_t + \varepsilon_{it} \qquad (3) \end{aligned}$$

Where;

ρ is a spatial autoregressive coefficient, determining how the dependent variable country i can influence the dependent variable of its neighboring country j. θ represents the spatial spillover effects of the explanatory variables. α and β are the intercept and slope coefficients c_i and μ_t

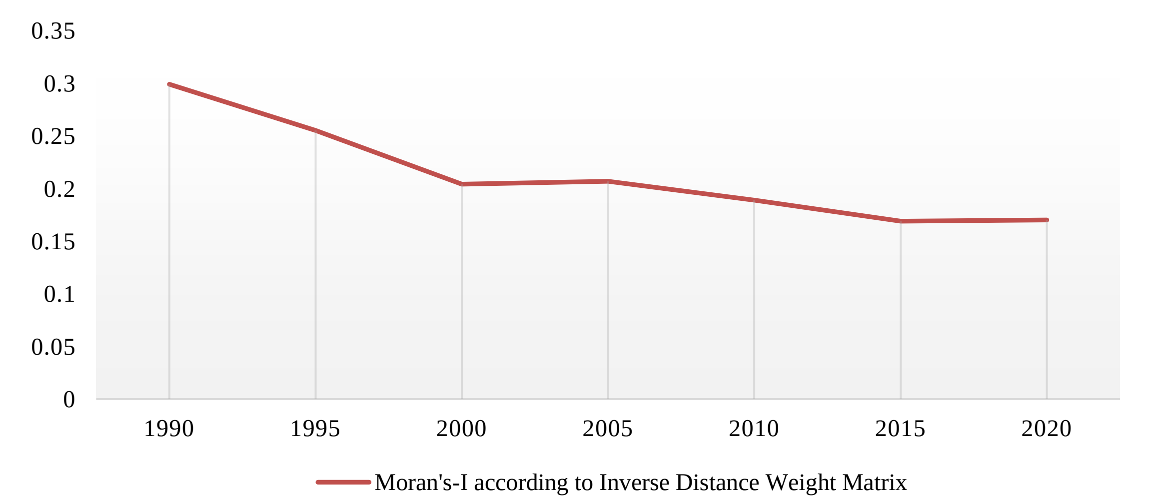
guarantees the time and fixed effects in the SDM. W_{ij} shows spatial weight matrix, captures the degree of spatial relationship between a country and its neighbors.

Findings and Discussion

Spatial Exploratory Analysis

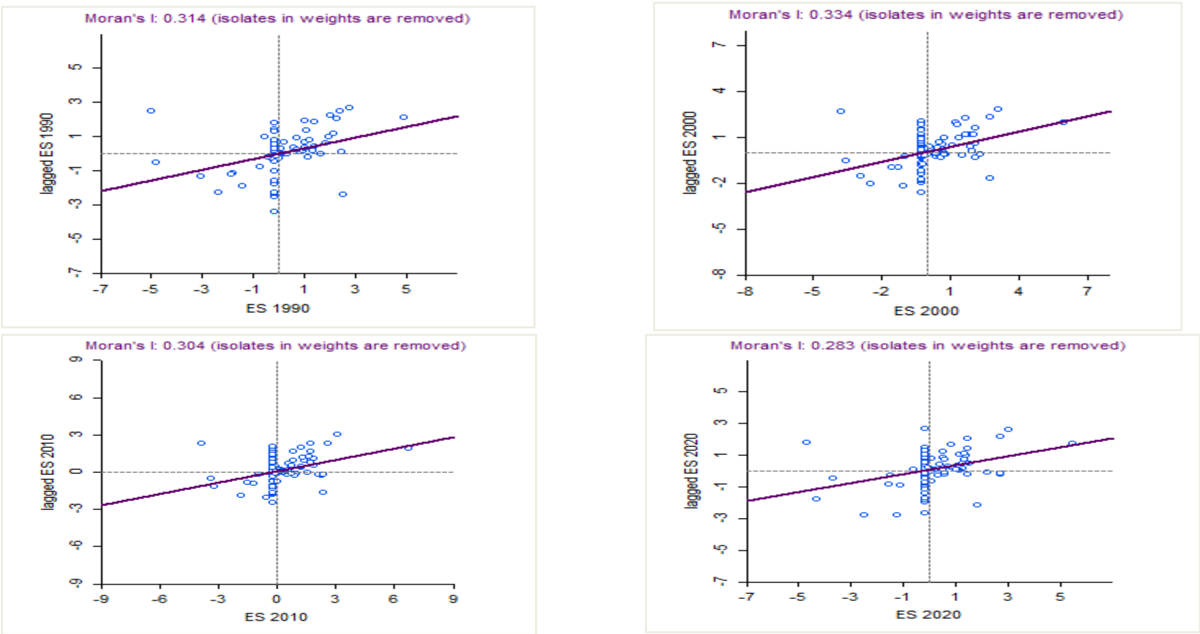
Figure 1 presents Moran's I scatterplots, revealing a positive and significant spatial dependence in environmental sustainability across the sampled countries. The global Moran's I values range from 0.170 to 0.299 over 1990–2022, indicating persistent clustering of countries with similar environmental health levels and confirming the relevance of a spatial econometric framework.

Figure 1: Global Moran's I for Environmental Deficit



The Local indicator of spatial association (LISA) cluster agglomeration map is shown in the figure 2.

Figure 2: Local Moran's I (LISA) Scatter Plots for Environmental Health Index (EH)



Source: Global Footprint Network (GFN) data; analysis conducted via GIS and GeoDa by Author

Summary Statistics

Table 2 presents descriptive statistics of the variables under consideration. Green Technological Innovation GI_{it} exhibited the highest volatility, while Globalization GB_{it} is least volatile. Control variables, such as Economic Development ED_{it} and Urbanization UR_{it} along with interaction terms $(GI * GB)_{\mathrm{it}}$, also showed high volatility, with Urbanization being the least volatile. Environmental Health Index EH_{it} has a mean of -1.490, with a standard deviation of 2.227 and range from -15.47 to 66.40. Green Technological Innovation GI_{it} show a mean of 13.369, with a standard deviation of 15.41 and range from 0.670 to 172.25. Economic Development (ED_{it}) had a mean of 908.949, with a minimum of 1.000 and a maximum of 1817.000, and a standard deviation of 516.232. Urbanization UR_{it} had a mean of 1.449, with minimum and maximum values of -3.146 and 12.771, respectively, and a deviation of 1.386. Globalization GB_{it} had a mean of 62.044, with minimum and maximum values of 15.000 and 95.000, respectively, and a deviation of 17.916. The Variance Inflation Factor (VIF) values indicate that multicollinearity is not a major issue in this analysis, with all VIF values well below the threshold of 10, suggesting that the variables are not highly correlated with each other.

Table 2: Summary Statistics

Variables	N	Mean	Std. dev.	Min	Max	VIF
EH_{it}	1980	2.013	2.227	-1.490	14.025	-------
GI_{it}	1980	13.369	15.410	0.670	172.255	4.01
ED_{it}	1980	908.949	516.232	1.000	1817.000	1.04
UR_{it}	1980	1.449	1.386	-3.146	12.771	1.17
GB_{it}	1980	62.044	17.916	15.000	95.000	1.06

Source: Author's calculations

Model Selection

The Spatial Durbin Model (SDM) was first estimated, followed by Wald tests rejecting its reduction to SAR or SEM. The Hausman test supported fixed effects, and model selection based on minimum AIC and SIC identified the SDM with spatial and time fixed effects as the preferred specification.

Table 3: Model Selection

Model	AIC	SIC
Spatial fixed effects	4114.583	4192.855
Time fixed effects	7679.949	7758.221
Spatial and time fixed effects	4073.06	4151.332
Robust Hausman test		
Suitability of a Random Vs Fixed effects by the Robust Hausman test Ho: difference in coefficients not systematic	$Chi^2(13) = 24.68\ (0.020)$ Ho: Rejected	
Wald test		
Suitability of SDM Vs SAR by Wald test Ho: SDM converge to SAR	$Chi^2\ (6) = 109.31\ (0.000)$ Ho: Rejected	
Suitability of SDM Vs SEM by Wald test Ho: SDM converge to SEM	$Chi^2\ (6) = 67.35\ (0.000)$ Ho: Rejected	

Note: ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. Corresponding p-values are reported in parentheses.

Global Spatial Dependence in Environmental Health Index (EH_{it})

Table 4 reports Moran's I results, confirming significant spatial dependence in the environmental health index across countries over 1990–2022 using distance-based weights, thereby justifying the use of spatial econometric methods.

Table 4: Moran's I for Environmental Health Index (EH_{it})

Years	Moran-I	Years	Moran's I
1990	0.140***	2010	0.153***
1995	0.137***	2015	0.154***
2000	0.136***	2020	0.136***
2005	0.154***	2022	0.136***

Note: ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. parentheses.

Spatial Decomposition Analysis

Estimating spatial direct, indirect impacts is essential even when main estimates are available, because they uncover how effects are distributed across countries (LeSage & Pace, 2009). Table 5 summarizes the decomposition analysis of direct and indirect (spillover effects) of green technological innovation on environmental health. The significantly negative local (-0.133) and global spill-over effects (-0.038) of GI_{it} shows that, green innovations are not improving but rather deteriorating environmental health in this context. The positive local (0.057) and global spillover (0.301) effects of GI_{it}^2, on EH_{it} suggest that green innovation becomes increasingly effective once a certain threshold is surpassed, aligning with the concept of diminishing marginal returns. The finings disclose an inverted U-shaped relationship between green technological innovations and environmental health index: early-stage adoption of green technologies can deteriorate environmental sustainability maybe due to high transitional costs, while after reaching a certain threshold level, green technologies meaningfully improve environmental sustainability at local and global level.

Table 5: Decomposition Analysis (Dependent Variable: EH_{it})

Variables	Direct	Indirect Effect	Total Effects
GI_{it}	-0.133*** (0.000)	-0.038 (0.003)	-0.171*** (0.000)
GI_{it}^2	0.057*** (0.000)	0.301*** (0.001)	0.358*** (0.000)
ED_{it}	-0.003*** (0.001)	0.002 (0.271)	-0.001*** (0.000)
UR_{it}	1.438* (0.065)	4.166*** (0.000)	5.605*** (0.000)
GB_{it}	-0.026 (0.397)	-0.426*** (0.007)	-0.452 (0.292)
$(GI * GB)_{it}$	0.123*** (0.000)	0.070 (0.718)	0.194*** (0.000)
ρ	------	-------	0.177*** (0.001)

Note: ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. Corresponding p-values are reported in parentheses.

Moderating Role of Globalization: Aspatial Framework

Following Chin, Marcolin, and Newsted (2003), an interaction term of green technological innovations and globalization $(GI * GB)_{it}$ is introduced. Green innovation GI_{it} exhibits positive and significant coefficients (0.570 and 0.572) for both fixed and random effect models, whereas globalization Gb_{it} remains positive but insignificant (0.014), represent that neither factor alone can improve environmental sustainability. In contrast, the interaction term $(GI * GB)_{it}$is negative and highly significant under fixed and random effect models, implying that globalization work as a moderator between green technological innovation and environmental sustainability by reversing its impartial detrimental effect. The consistency across fixed and random effect models confirms the robustness of the moderating role of globalization which is in line with existing empirical evidence (Ahmad & Wu, 2022; Ahmad et al., 2022).

Table 6: Regression Results of Fixed and Random Effects (Dependent Variable: EH_{it})

Variable	Fixed effects	Random effects
GI_{it}	0.570***	0.572***
	(0.000)	(0.000)
ED_{it}	0.019***	0.019**
	(0.025)	(0.021)
UR_{it}	-0.049***	-0.046***
	(0.003)	(0.005)
GB_{it}	0.014	0.014
	(0.494)	(0.457)
$(GI * GB)_{\mathrm{it}}$	-0.282***	-0.284***
	(0.000)	(0.000)
R^2	0.497	0.498

Note: ***, **, and * shows significance at 1%, 5%, and 10% levels. The p-values are stated in parentheses.

Following Jenatabadi (2014), Sardeshmukh and Vandenberg (2017) and Liu et al. (2025), we employ Panel Structural Equation Modeling (SEM) to further check the moderating effects of globalization. In this regard, two more specifications are estimated. Specification 1 measures the direct effects of green technological innovation and globalization, while Specification 2 includes the interaction $(GI * GB)_{\mathrm{it}}$, with model selection guided by AIC and BIC.

Table 7 presents the robust empirical evidence of the moderating effects of globalization. Green technological innovation and globalization shows significant negative effects on environmental sustainability separately, while after interaction, they reduce the magnitude of green technological innovations (0.656), renders globalization insignificant (0.021), and yields a negative and highly significant effect (–0.373). The interaction model displays good fit, shown by the lower AIC (11834.25) and BIC (11873.39) statistics, approving the moderating role of globalization. These results align with the prior empirical evidences (Rani et al., 2022; Ojeyinka & Osinubi, 2022; Ehigiamusoe et al., 2024), designate that the environmental effects of green technological innovations fluctuate systematically with the level of globalization.

Table 7: Regression Results of Structural Equation Modeling (SEM) (Dependent Variable: EH_{it})

Variable	SEM without Interaction Effect	SEM with Interaction Effect
GI_{it}	0.699*** (0.000)	0.656*** (0.000)
ED_{it}	0.020*** (0.002)	0.041*** (0.003)
UR_{it}	-0.014*** (0.384)	-0.011*** (0.497)
GB_{it}	0.035*** (0.028)	0.021 (0.180)
$(GI * GB)_{it}$	--------	-0.373*** (0.000)
AIC	**11866.58**	**11834.25**
BIC	**11900.12**	**11873.39**

Note: ***, **, and * shows significance at 1%, 5%, and 10% levels. The p-values are stated in parentheses.

The moderating effects of globalization established through three important observations: (a) the significant interaction term, (b) the alterations in direct effects with the introduction of interaction, and (c) the improved model fit statistics. These results together authorize that globalization work as a significant moderating factor in determining the relationship between green technological innovations and environmental sustainability.

Moderating Role of Globalization: Spatial Framework

To explore the role of Globalization (GB_{it}) as a moderator in more detail, we examine it within a spatial econometric framework, recognizing that environmental and policy impacts often extend beyond national borders. Table 8 present the results of Spatial Durbin Model (SDM) provide convincing evidence of globalization's moderating impact. We have presented two models; one without interaction term and other with interaction term.

In the first model having no interaction term, green innovations (GI_{it}) shows a strong positive coefficient (0.866), indicate its beneficial impact on environmental health (EH_{it}). However, when the interaction term $(GI * GB)_{it}$ is introduced, the coefficient of GI_{it} becomes slightly more positive (1.084), while the interaction term itself remains significantly negative (-0.299). However, the coefficient of GI_{it}^2 remains negative (-0.402 and -0.289) in both models, but the highly significant in the model having interaction term. Similarly, the spatial effects of the specification are highly significant, having interaction term shows beneficial impact of GI_{it} on EB_{it}. This shift proposes that GB_{it} enhances the positive effect of GI_{it}, reinforcing their capacity to improve environmental sustainability. Furthermore, the coefficient of GB_{it} alone remains positive in both models, becomes statistically significant only in the second model having an interaction term (0.076), underscoring its conditional status.

In the model without the interaction term, ρ is statistically insignificant, inferring weak spatial spillovers. However, in the interaction model, ρ becomes highly significant, demonstrating that the moderating role of globalization not only strengthens the direct relationship between GI_{it} and EB_{it}, but also enhances spatial interdependencies. This finding highlights the significance of taking globalization in spatial policy design, as its presence can expand the regional diffusion of green innovation benefits.

Table 8: Moderation Through Spatial Model (Dependent Variable: EH_{it})

Variable	SDM without Interaction Effect	SDM with Interaction Effect
GI_{it}	0.866*** (0.000)	1.084*** (0.000)
GI_{it}^2	-0.402*** (0.005)	-0.289*** (0.000)
GB_{it}	0.087 (0.000)	0.076*** (0.000)
$(GI * GB)_{it}$	-------	-0.299*** (0.000)
$Spatial\ rho\ (\rho)$	0.053 (0.337)	0.145*** (0.000)
$W * GI_{it}$	-0.128** (0.051)	-0.480*** (0.000)
$W * GI_{it}^2$	0.008*** (0.863)	-0.117** (0.000)
$W * GB_{it}$	0.439** (0.000)	0.470** (0.000)
$W * (GI * GB)_{it}$	-------	0.406*** (0.000)

Note: ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. Corresponding p-values are reported in parentheses.

Robustness Analysis

To ensure the reliability of the empirical findings, we conducted robustness checks. First, we re-estimated all empirical models using an alternative spatial weight matrix (K-Nearest Neighbors) to test the sensitivity of parameter estimates. Further, wwe have substituted the policy variable; the green technological innovation (GI_{it}) with an alternate measure; the green energy (RE_{it}) and estimated another specification, which also produced robust results. These robustness checks support the key hypothesis that GI_{it} has linear and non-linear effects on HT_{it}.

Spatial Dependence of environmental health $(\mathbf{HT_{it}})$ with Alternative Spatial Weight Normalization Criteria

We applied the K-Nearest Neighbors method with KNN=5 to generate a weight matrix. Global Moran's-I values were computed using these two weight matrices, and the results are summarized in Table 9. Subsequently, we used these alternative weight matrices in regression analysis, and the results demonstrate that the Moran's I values of environmental sustainability (EH_{it}) aligns closely with those obtained using the distance weight matrix, confirming the consistency and robustness of our earlier findings on the spatial dependence.

Table 9: Moran's I of Environmental Health Index *(EH_{it})* based on KNN Weight Matrix

Years	Moran-I	Years	Moran's I
1990	0.508***	2010	0.548***
1995	0.507***	2015	0.544***
2000	0.541***	2020	0.542***
2005	0.538***	2022	0.541***

Note: ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. Corresponding p-values are reported in parentheses. (K-Nearest Weight Matrix (K=5km)

Empirical Results with K-Nearest Weight Matrix Normalization

Table 10 presents the robustness of the decomposition analysis of the Spatial Durbin Model (SDM). The empirical findings are consistent with different spatial weight matrices.

Table 10: Spatial Effects Based on KNN Spatial Weight (Dependent Variable: EH_{it})

Variables	Direct Effect ($\rho = 0$)	Indirect Effect ($\rho \neq 0$)	Total Effects
GI_{it}	-0.128** (0.000)	-0.589*** (0.000)	-0.717*** (0.000)
GI_{it}^2	0.072*** (0.000)	0.749*** (0.000)	0.822*** (0.000)
ED_{it}	-0.002*** (0.000)	0.009*** (0.027)	-0.011*** (0.010)
UR_{it}	0.894*** (0.000)	4.113 (0.000)	5.008*** (0.000)
GB_{it}	-0.010*** (0.661)	0.873*** (0.000)	0.862*** (0.000)
ρ	--------	--------	0.238*** (0.000)

Note: ***, **, and * shows significance at 1%, 5%, and 10% levels. The p-values are stated in parentheses.

Conclusion and Policy Recommendations

This study analyzes the spatial spillover effects of green technological innovation (GI) on environmental sustainability using the environmental health index (EH) as a proxy. The study also examines the moderating role of globalization (GB) across 60 countries over the period of 1990 to 2022. The findings show that green technological innovations (GI) non-linearly affecting environmental health at both local (domestic) and global scales, with environmental benefits occurring only after a certain threshold level. Green patents and green energy, significantly improves air quality, sanitation, drinking water, and waste management. Environmental sustainability is shaped by both domestic innovation and spatial spillovers, although local spillovers dominate, highlighting the significance of geographic proximity. Globalization (GB) work as a moderator rather than a direct determinant of environmental sustainability. While globalization (GB) alone adversely affects environmental health, its interaction with green technological innovation (GI) reverses this effect, enhancing both domestic and cross-border environmental gains. This moderating role is established across FE, RE, SEM model and spatial models estimates. Overall, the empirical findings underline that the environmental health of green technological innovation (GI) depends on the degree of economic integration and international green technological diffusion across globe.

The study suggests that green technological innovation (GI) and globalization (GB) should be pursued jointly rather than in isolation. Governments should sustain long-term investment in green innovations, particularly in renewable energy, clean technologies, and green R&D to ensure innovation surpasses the threshold required to generate environmental benefits. At the same time, globalization (GB) should be strategically managed by aligning trade, foreign investment, and industrial policies with environmental objectives, so that globalization (GB) facilitates green technology transfer rather than pollution relocation. Strengthening domestic innovation systems and regulatory capacity can maximize local environmental gains, while enhanced regional cooperation, harmonized environmental standards, and cross-border knowledge sharing can amplify spatial spillovers. Integrating environmental conditions into globalization (GB) frameworks, such as green trade agreements and environmentally screened investment policies can ensure that globalization (GB) acts as a catalyst for environmental sustainability rather than a constraint.

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Appendices

Appendix A: List of the Sample Countries

S.No.	Name of the Country	S.No.	Name of the Country
1	Australia	31	Korea Republic
2	Argentina	32	Luxembourg
3	Austria	33	Malaysia
4	Azerbaijan	34	Malta
5	Bangladesh	35	Mauritius
6	Belarus	36	Mexico
7	Belgium	37	Morocco
8	Brazil	38	Nepal
9	Bulgaria	39	Netherlands
10	Canada	40	New Zealand
11	Chile	41	Norway
12	China	42	Pakistan
13	Colombia	43	Philippines
14	Cyprus	44	Poland
15	Czech Republic	45	Portugal
16	Denmark	46	Romania
17	Finland	47	Russian Federation
18	France	48	Saudi Arabia
19	Germany	49	Singapore
20	Greece	50	Slovak Republic
21	Hungary	51	Spain
22	India	52	Sweden
23	Indonesia	53	Switzerland
24	Iran	54	Thailand
25	Ireland	55	Turkey
26	Israel	56	Ukraine
27	Italy	57	United Kingdom
28	Japan	58	United States
29	Jordan	59	Uzbekistan
30	Kazakhstan	60	Vietnam