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The Innovation–Sustainability Paradox: Nonlinear Evidence from a Global Panel

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ABSTRACT

Research Originality: Departing from studies that assume a linear or monotonic innovation–sustainability link, this study is among the first to provide global panel evidence of a nonlinear, income-differentiated innovation–sustainability paradox, using an SDG index adjusted to avoid conceptual overlap with human development measures, and finds robust results from lagged identification.

Research Objectives: This study examines whether innovation consistently promotes sustainable development across 88 countries from 2018 to 2023, testing for nonlinearity and income-group heterogeneity.

Research Methods: A balanced panel fixed-effects framework estimates three specifications using an adjusted SDG index, namely linear, quadratic, and interaction models. Robustness is assessed via lagged GII, with structural heterogeneity examined through income-group subgroup analysis.

Empirical Results: GDP per capita positively predicts SDG performance with diminishing returns. GII follows an inverted U-shaped pattern (GII* ≈ 21.25), confirming the innovation–sustainability paradox. Most countries already operate past the turning point. Among Middle- and Low-Income economies, the threshold is higher (GII* ≈ 40.50), whereas High-Income economies exhibit a structural plateau.

Implications: Innovation policy must be calibrated to the stage of development. Advanced economies should redirect mature innovation systems toward sustainability objectives, while developing economies should expand capacity with directionality embedded from the outset.

Keywords: Global Innovation Index; sustainable development goals; nonlinear panel; inverted U-shaped; income heterogeneity

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INTRODUCTION

Sustainable development remains the benchmark for modern development policy, yet the progress towards the SDGs has become increasingly fragile. The 2025 global SDG review indicates that only around 18% of the targets are on track, with large proportions stagnating or regressing below the 2015 baseline. Several fundamental objectives, including hunger reduction, health, education, and climate action, continue to fall behind schedule (United Nations, 2025). The central analytical challenge is therefore not whether sustainable development is desirable, but which structural factors most reliably accelerate SDG achievement across diverse national settings (Malekpour et al., 2023).

Among the structural factors most frequently invoked in this debate is innovation. Innovation can improve productivity, enable technological upgrading, support cleaner production, and expand renewable-energy solutions, which makes it widely regarded as a strategic lever for sustainable development. Recent literature increasingly frames innovation policy not merely as a competitiveness tool, but as an instrument for transformative change capable of addressing societal grand challenges (Schot & Steinmueller, 2018; Geels et al., 2023; Mariani et al., 2022). However, the innovation-sustainability relationship is far from automatic. Innovation does not inherently guarantee ecological balance or social inclusion because its developmental contribution depends on how it is framed, governed, and directed. Recent SDG-oriented research confirms that high innovation performance does not necessarily translate into balanced progress across the full social, environmental, and institutional architecture of the SDGs (Pansera & Owen, 2018; Dzhunushalieva & Teuber, 2024; Suchitwarasan et al., 2024).

Two additional sources of complexity further challenge the assumption of a straightforward innovation-sustainability link. First, economy-wide rebound effects suggest that efficiency improvements from innovation often do not translate proportionally into lower energy use or reduced environmental pressure, because increases in production and consumption partially offset these gains (Brockway et al., 2021; Andrew & Pigosso, 2024). Second, recent studies report inverted-U and other nonlinear patterns in the innovation-sustainability relationship, indicating that innovation generates positive returns up to a threshold beyond which complexity, cost, and system-level trade-offs begin to weaken its net contribution (Leyva-de la Hiz & Bolívar-Ramos, 2022; H. Li et al., 2024). Alongside innovation, economic capacity constitutes a foundational determinant of SDG achievement, as higher-income countries typically possess greater fiscal space, stronger infrastructure, and broader access to social investment that enables sustainability-oriented spending (Sachs et al., 2020; Naqvi et al., 2025; Guillamón et al., 2025). However, even economic capacity exhibits diminishing returns at higher development levels, which raises parallel questions about the sustainability dividend of growth itself (Hickel, 2019).

Despite growing scholarly interest in the innovation-sustainability nexus, three important gaps persist in the literature. First, most empirical studies rely on narrow outcome measures such as carbon emissions or ecological footprints rather than comprehensive SDG performance metrics, which limits the generalisability of findings

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to the broader sustainability agenda. Second, the dominant empirical approach assumes a linear relationship between innovation and sustainability, and implicitly assumes that innovation is uniformly good, regardless of intensity. This assumption may hide threshold effects and diminishing returns that are theoretically plausible and policy relevant. Third, while Omri (2020) first raised the possibility that the sustainability effect of innovation varies systematically across income groups, this income-differentiated dimension remains underexplored in globally representative panel settings. Together, these gaps leave the central policy question unresolved. Does innovation reliably promote sustainable development as its intensity increases, or does its contribution weaken beyond a certain threshold?

This study addresses these gaps by examining the innovation-sustainability relationship across 88 countries over 2018-2023 using a panel fixed-effects framework that explicitly tests for nonlinear and income-differentiated effects. This study estimates three sequential specifications, namely a baseline linear model, a quadratic model that tests for diminishing returns in GII and GDP per capita, and an interaction model that assesses whether human development moderates the innovation effect. Lagged GII specifications serve as robustness checks. This study contributes empirical support for an innovation-sustainability paradox by demonstrating that the GII-SDG relationship follows an inverted-U pattern, with most countries already operating in the diminishing-returns region, and by showing that this paradox manifests with income-differentiated structural features that carry distinct policy implications for advanced and developing economies in the final years of the 2030 Agenda. Unlike Omri (2020), who documents income-differentiated effects of technological innovation on sustainability without explicitly modeling the underlying nonlinear turning point, or Le et al. (2025), who examine a linear innovation-led development pathway, this study provides a systematic estimate of the innovation–sustainability threshold and its income-conditioned variation within a globally representative fixed-effects framework.

METHODS

This study uses a balanced panel dataset of 88 countries observed annually from 2018 to 2023, yielding 528 observations. The sample period is bounded by the joint availability of all four data sources. The lower bound of 2018 corresponds to the earliest year for which consistent and complete observations across the SDG index, World Bank GDP estimates, WIPO's Global Innovation Index, and UNDP's Human Development Index were simultaneously available for the full country set. The upper bound of 2023 reflects a binding data constraint: the HDI series had not been updated beyond 2023 by UNDP at the time of data collection. Extending the panel to 2024 or 2025 would introduce systematic missingness in HDI that risks selection bias and would undermine the within-country fixed-effects identification strategy. The resulting six-year window (T = 6; N = 88; 528 observations) provides sufficient temporal variation for the nonlinear fixed-effects specifications estimated in this study. The dependent variable is an adjusted SDG index that excludes Goals 3 (Health) and 4 (Education) to reduce conceptual overlap with the Human Development Index, which is included as an explanatory variable. The primary independent variables are the natural logarithm of GDP per capita in purchasing power parity terms (LNGDPPC), the Global Innovation Index (GII), and the Human Development Index (HDI). Data come from four sources: the Sustainable Development Reports, the World Bank database, the World Intellectual Property Organization (WIPO), and the United Nations Development Program (UNDP). Table 1 presents complete variable definitions and measurements.

Table 1. Definitions and Measurements of The Variables

Variables	Definition	Measurement
SDG Adj	Annual Sustainable Development Goals Index, excluding Goal 3 (Health) & 4 (Education) to reduce potential overlap with explanatory variables	Score (0-100)
LNGDPPC	Gross Domestic Product per capita in Purchasing Power Parity terms, capturing economic capacity across countries (log-transformed in estimation)	Constant international USD (log)
$LNGDPPC^2$	Squared term of the natural logarithm of GDP PPP/ Capita, included to capture potential nonlinear effects of economic development on sustainable development	$(\log$ GDP PPP/ Capita$)^2$
GII	Annual Global Innovation Index of 88 countries, reflecting national innovation capacity and performance across multiple dimensions	Score (0-100)
GII^2	Squared term of the Global Innovation Index, used to test for diminishing returns and nonlinear relationships between innovation and sustainable development	Index squared
HDI	Annual Human Development Index of 88 countries, representing composite achievements in income, education, and life expectancy	Score (0-1)
GII_HDI	Interaction term between the Global Innovation Index and the Human Development Index, capturing the conditional effect of innovation depending on the level of human development	GII × HDI

This study estimates three sequential specifications to capture linear, nonlinear, and conditional relationships within a unified analytical framework:

$$SDG\ Adj_{it} = \beta_0 + \beta_1 LNGDPPC_{it} + \beta_2 GII_{it} + \beta_3 HDI_{it} + \epsilon_{it} \tag{1}$$

$$SDG\ Adj_{it} = \beta_0 + \beta_1 LNGDPPC_{it} + \beta_2 LNGDPPC^2_{it} + \beta_3 GII_{it} + \beta_4 GII^2_{it} + \beta_5 HDI_{it} + \epsilon_{it} \tag{2}$$

$$SDG\ Adj_{it} = \beta_0 + \beta_1 LNGDPPC_{it} + \beta_2 GII_{it} + \beta_3 HDI_{it} + \beta_4 GII\_HDI_{it} + \in_{it} \tag{3}$$

The baseline model (1) estimates the average linear association between structural development factors and adjusted SDG performance. The nonlinear model (2) introduces quadratic terms for LNGDPPC and GII to test for diminishing returns, consistent with the innovation-sustainability paradox hypothesis. The interaction model (3) assesses whether the sustainability effect of innovation depends on the level of human development.

Panel fixed effects specification is selected following Chow and Hausman tests. The results show that the Chow test rejects pooled OLS, and the Hausman test indicates that fixed effects is preferred over random effects. Fixed effects estimation controls for time-invariant country-specific heterogeneity that may correlate with the explanatory variables, thereby reducing omitted variable bias (Baloch et al., 2019). To assess whether the main findings are sensitive to potential simultaneity bias, additional specifications

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replace contemporaneous GII with one-period lagged values. White cross-section robust standard errors address heteroskedasticity and contemporaneous cross-sectional dependence across the heterogeneous country sample (Jiakui et al., 2023).

RESULTS AND DISCUSSION

This study finds that the innovation–sustainability relationship is nonlinear and income-differentiated rather than uniformly positive, providing cross-country panel evidence for an innovation–sustainability paradox. GDP per capita exerts a robust positive effect on adjusted SDG performance across all specifications, yet this contribution diminishes at higher income levels. The Global Innovation Index follows an inverted-U relationship with sustainable development, with a turning point near the lower bound of the sample distribution, indicating that most countries already operate in the diminishing-returns region where further innovation intensity generates progressively smaller sustainability gains. Robustness checks using lagged GII specifications confirm that reverse causality does not drive this pattern. Subgroup analysis further reveals that the paradox is income-differentiated, with developing economies retaining positive innovation-sustainability returns up to a substantially higher threshold. In contrast, advanced economies exhibit a structural plateau where aggregate innovation volume no longer drives SDG performance in a statistically detectable way.

Table 2. Descriptive Statistics of The Variables 2018-2023

Variable	Mean	Std. Dev.	Min.	Max.
SDGs Adj.	68.88	8.34	50.04	84.52
LNGDPPC	9.81	1.11	7.15	11.88
GII	33.82	11.98	11.6	64.2
HDI	0.77	0.15	0.39	0.97

Table 2 shows substantial cross-country variation in all variables. The adjusted SDG score ranges confirm sufficient outcome variation to support cross-country estimation, while GII ranges and mean indicate that the sample spans countries at very different stages of innovation-system maturity. Importantly, the strong pairwise correlations among LNGDPPC, GII, and HDI reported in Table 3, particularly the near-perfect positive correlation between income and human development, anticipate multicollinearity challenges in the full-sample estimation that are addressed through sequential specification and subgroup analysis.

Moving beyond the descriptive profile, Table 4 reports the baseline fixed-effects estimates. This model uses adjusted SDG scores as the dependent variable, with GDP per capita, innovation capacity, and human development as the primary independent variables to determine the average linear association between these structural factors and SDG performance, prior to incorporating nonlinear terms and interaction effects.

Table 4 reports the baseline fixed-effects estimates. The model is jointly significant and yields a high adjusted R^2, reflecting the combined explanatory power of the structural variables alongside cross-country fixed effects. Economic capacity exerts a strong positive effect on adjusted SDG performance, confirming that higher-income countries possess greater fiscal space and institutional capacity to finance sustainability-oriented investment, consistent with recent cross-country evidence (Guillamón et al., 2025; Naqvi et al., 2025). By contrast, GII enters with a negative and statistically significant coefficient, indicating that in a linear specification, higher innovation intensity associates with lower SDG performance (Le et al., 2025).

Table 3. Correlation Matrix of the Variables

Variable	SDGs Adj	LNGDPPC	GII	HDI
SDGs Adj.	1.000			
LNGDPPC	0.676	1.000		
GII	0.766	0.764	1.000	
HDI	0.770	0.955	0.814	1.000

Table 4. Estimated Results of the Baseline Model

Variable	Coefficient	t-Statistic	Prob.
Constant	45.647	14.943	0.000
LNGDPPC	2.553	9.169	0.000
GII	-0.070	-5.083	0.000
HDI	0.737	0.219	0.826
Adjusted R-Square	0.995		
F-Statistic	1305.819		
Prob. (F-Statistic)	0.000		

Rather than suggesting that innovation harms sustainability, this result signals that a linear framework is insufficient to capture the full structure of the relationship, which directly motivates the nonlinear specification estimated in Table 5. HDI does not emerge as a statistically significant predictor once income and innovation are jointly controlled for, an expected result given the near-perfect correlation between HDI and LNGDPPC (r = 0.955) documented in Table 3, which prevents the fixed-effects estimator from precisely separating their independent contributions. All subsequent HDI results should be interpreted in light of this structural overlap.

Following the preliminary regression analysis, Table 5 displays the outcomes of a nonlinear model, incorporating squared terms for LNGDPPC and GII. Consequently, the nonlinear model offers a more refined understanding of the innovation–sustainability relationship than the initial linear framework. Table 5 reveals that the innovation-sustainability relationship follows an inverted-U pattern rather than a monotonic one. GDP per capita retains a strong positive effect on adjusted SDG performance while its squared term enters negatively, confirming that economic capacity drives sustainability outcomes with diminishing returns at higher income levels, consistent with environmental

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Kuznets curve interpretations (Stern, 2017; Nathaniel, 2021). More substantively, GII enters positively while its squared term is negative and statistically significant, indicating that innovation contributes to sustainable development up to a threshold beyond which its marginal effect weakens.

Table 5. Estimated Results of the Nonlinear Model

Variable	Coefficient	t-Statistic	Prob.
Constant	-26.529	-2.199	0.028
LNGDPPC	16.925	7.214	0.000
$LNGDPPC^2$	-0.705	-6.167	0.000
GII	0.085	2.082	0.037
GII^2	-0.002	-3.406	0.001
HDI	-2.582	-0.777	0.437
Adjusted R-Square	0.995		
F-Statistic	1383.352		
Prob. (F-Statistic)	0.000		

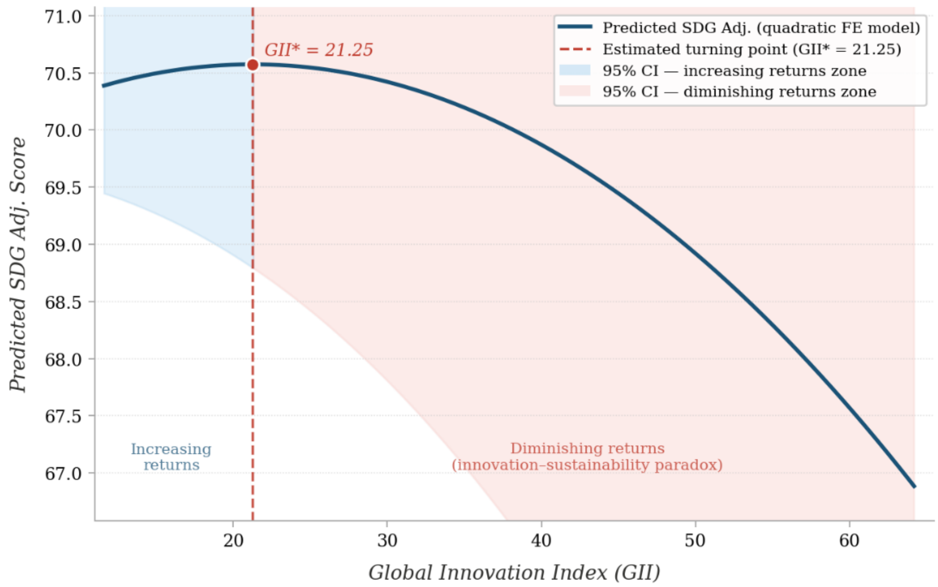
The turning point is estimated as follows:

$$GII^{*} = -\frac{\beta(GII)}{2\beta(GII^{2})} = -\frac{0.085}{2(-0.002)} = -\frac{0.085}{-0.004} \approx 21.25 \qquad (4)$$

Because this value falls near the lower bound of the observed GII range (11.6-64.2), most countries in the sample already operate in the diminishing-returns region where further innovation intensity generates progressively smaller sustainability gains. Figure 1 plots the predicted nonlinear contribution of GII to adjusted SDG performance across the observed range, confirming that the inverted-U pattern is economically meaningful rather than a statistical artifact.

This finding extends and nuances prior evidence on the innovation-sustainability nexus. Omri (2020) shows that the sustainability effect of technological innovation varies systematically by income group, while Chaparro-Banegas et al. (2023) demonstrate that innovation facilitators promote SDG achievement. However, growth limits and ecosystem boundaries constrain their effects. The present study adds that this variation operates within a nonlinear structure where innovation remains beneficial, but its sustainability payoff diminishes as intensity rises. At a more granular level, Leyva-de la Hiz & Bolívar-Ramos (2022) document a similar inverted-U relationship between green innovative activities and firm performance, and Li et al. (2024) describe a green innovation paradox in which carbon-emission reduction efforts generate diminishing technological returns beyond a threshold. A plausible mechanism connecting these patterns is the rebound effect. Efficiency gains from innovation often trigger additional production and consumption that partially offset environmental benefits (Andrew & Pigosso, 2024; Mallari et al., 2025). This evidence supports the interpretation that sustainable development outcomes depend not on how much innovation a country produces, but on whether that innovation is directed toward social and ecological objectives rather than productivity and scale expansion alone (Dzhunushalieva & Teuber, 2024; Suchitwarasan et al., 2024).

Figure 1. Innovation-Sustainability Paradox: Evidence of Diminishing Returns



Source: author's calculation

Table 6 presents the interaction model estimates. GII retains a negative and statistically significant direct effect, consistent with the baseline results. This suggests that innovation does not automatically promote sustainable development in the absence of directional governance (Zadegan & Ghazinoory, 2026). This finding is further supported by Cetinguc et al. (2023), who demonstrate, using GII and HDI jointly across income groups, that income level itself absorbs the moderating role of human development in innovation-outcome relationships. Agarwalla & Sahu (2024) also point out that innovation and human capital each make a non-synergistic contribution to sustainable development. This explains why the GII and HDI interaction term is not significant. The two variables operate independently, rather than moderating one another.

Table 6. Estimated Results of the Interaction Model

Variable	Coefficient	t-Statistic	Prob.
Constant	48.325	13.563	0.000
LNGDPPC	2.570	9.233	0.000
GII	-0.148	-2.677	0.001
HDI	-3.386	-0.771	0.441
GII_HDI	0.108	1.455	0.146
Adjusted R-Square	0.995		
F-Statistic	1294.797		
Prob. (F-Statistic)	0.000		

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Furthermore, published official data sources do not provide sufficient evidence of a systematic moderating role for human development in the full sample (Del-Aguila-Arcentales et al., 2023). The most plausible explanation for the null GII_HDI result is the consistency with the structural overlap documented in Table 4. When LNGDPPC already absorbs most of the developmental information contained in HDI, compounding multicollinearity further suppresses any detectable conditional moderation through the interaction term.

Table 7. Robustness Check Results: Lagged GII Specifications (RC1 and RC2)

Variable	RC1 Lag-Linear	RC2 Lag-Nonlinear
Constant	53.216***	-31.634**
LNGDPPC	2.062*	19.078***
LNGDPPC^2	–	-0.837***
GII t-1	-0.058**	0.073*
GII^2 t-1	–	-0.002***
HDI	-3.199	-6.620*
Turning point GII* t-1	≈ 20.24	
Adj. R-Square	0.997	
Observations	440	
SE Method	White diagonal	

Note(s): ***, **, and * indicate significance at 1%, 5% and 10% levels respectively
Both specifications are estimated using cross-section fixed effects over the reduced sample 2019–2023 (T=5), following one-period lag transformation of GII. White diagonal standard errors are applied to address heteroskedasticity.

Table 7 reports the robustness check results using one-period lagged GII specifications. RC1 confirms that the negative linear association between innovation capacity and adjusted SDG performance persists when GII is lagged, ruling out contemporaneous simultaneity as a driver of the baseline result. RC2 confirms that the inverted-U relationship documented in the nonlinear model is likewise robust. The quadratic structure is preserved, and the estimated turning point at GII* ≈ 20.24 remains nearly identical to the contemporaneous estimate, confirming structural stability across specifications. The near-identical turning points across contemporaneous and lagged specifications indicate that the innovation-sustainability paradox reflects a genuine temporal mechanism rather than a statistical artifact of reverse causality (Brockway et al., 2021; Le et al., 2025).

Table 8 presents the subgroup estimates by World Bank income classification. For Middle- and Low-Income economies, the inverted-U relationship is statistically confirmed. GII enters positively while its squared term enters negatively, yielding an estimated turning point of GII* ≈ 40.50. Because most developing economies in the sample operate below this threshold, they remain in the ascending segment of the innovation-sustainability curve where incremental innovation capacity continues to generate positive sustainability returns. This result extends Omri (2020), who shows that the sustainability dividend of technological innovation is stronger and more direct in developing economies, by locating this advantage within the specific nonlinear structure of the relationship. Economic capacity likewise retains its positive and diminishing-returns pattern in this subgroup, indicating that both income growth and innovation remain active structural drivers of SDG performance for developing economies. The negative marginal significance of HDI here reflects a collinearity-induced sign reversal in the presence of LNGDPPC, consistent with the structural overlap established in Table 4, rather than a genuine adverse human development effect (Soergel et al., 2021).

Table 8. Subgroup Analysis: Nonlinear Model by World Bank Income Group

Variable	Full Sample	High Income	Middle and Low Income
Constant	-26.529**	90.034***	-37.349*
LNGDPPC	16.925***	-2.625	20.176***
$LNGDPPC^2$	-0.705***	0.034	-0.941***
GII	0.085**	0.074	0.127**
GII^2	-0.002***	-0.001	-0.002*
HDI	-2.582	8.597	-6.411*
Turning point GII* t-1	≈ 20.24	≈ 29.88 (ns)	≈ 40.5
Adj. R-Square	0.995	0.998	0.995
Observations	528	210	318
Countries	88	35	53

Note(s): ***, **, and * indicate significance at 1%, 5% and 10% levels respectively

All specifications use cross-section and period fixed effects with White cross-section robust standard errors. Full sample results reproduced from Table 5. Income group classification follows World Bank FY2026 definitions. (ns) = turning point not statistically meaningful due to insignificant GII coefficients in the High-Income subgroup.

For High Income economies, the pattern diverges markedly. None of the structural regressors reach conventional significance thresholds in the within-country estimation. The variation in SDG scores within developed countries is very small, making it difficult for fixed effects to detect any marginal effects. This result is consistent with Masali et al. (2026), who demonstrate that high-income countries are approaching SDG saturation ceilings, leaving little marginal room for innovation intensity alone to drive further improvement within the observed period. Manzoor et al. (2023) use a fixed-effects panel dataset across income groups for innovation and outcomes in innovative countries, and support the argument that the effects of innovation differ structurally across income groups. Chaparro-Banegas et al. (2023) and Kroll et al. (2019) also observe that even for innovation-intensive countries, ecological limits and structural growth conditions constrain the sustainability dividend of further innovation, while Dzhunushalieva & Teuber (2024) show that high innovation performance does not automatically translate into balanced progress across the full SDG architecture. Collectively, these studies suggest that short-run variation in aggregate innovation volume no longer drives SDG performance in a statistically detectable manner. Although a turning point of GII* ≈ 29.88 can be arithmetically derived from the High-Income coefficients, it carries no substantive interpretation given the statistical insignificance of the underlying estimates.

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Taken together, the four estimation stages challenge the conventional assumption that more innovation, more income, and more human development will automatically and indefinitely improve sustainable development performance. The evidence supports a structural-development perspective in which SDG achievement depends on how economic capacity, innovation systems, and human capabilities are configured relative to sustainability objectives, rather than on their accumulation alone. Economic growth remains necessary but subject to diminishing sustainability returns. Innovation is productive but not inherently sustainability-enhancing. Human development is foundational but largely indirect in its observable statistical contribution once other structural conditions are controlled for. The pathway to SDG progress is therefore not a linear sequence from income accumulation to innovation intensity to sustainability outcomes, but a contingent and income-differentiated process in which the developmental value of innovation depends critically on its direction, governance, and alignment with the full social and ecological architecture of the 2030 Agenda (Schot & Steinmueller, 2018; Geels et al., 2023). The capability-building strategies must embed sustainability directionality from the outset and integrate with investments in human capital and institutional effectiveness (Kirchherr et al., 2023; OECD, 2024; World Bank, 2024). Across both contexts, human development should be positioned as foundational structural infrastructure for sustainability-oriented transformation rather than as a residual policy objective (UNDP, 2024).

CONCLUSION

This study examined whether innovation consistently promotes sustainable development across 88 countries from 2018 to 2023 using a panel fixed-effects framework. Four findings emerge. First, GDP per capita exerts a robust positive effect on adjusted SDG performance, subject to diminishing returns at higher income levels. Second, the Global Innovation Index follows an inverted-U pattern with a turning point at GII* ≈ 21.25, confirmed by lagged specifications at GII* ≈ 20.24, providing empirical support for an innovation-sustainability paradox in which most countries already operate in the diminishing-returns region. Third, HDI does not emerge as a statistically significant independent predictor in the full sample, most plausibly owing to its strong structural overlap with income. Fourth, the paradox is income-differentiated. Middle- and Low-income economies retain a higher turning point at GII* ≈ 40.50 and continue to benefit from innovation capacity expansion. In contrast, High-income economies exhibit a structural plateau where aggregate innovation volume no longer drives SDG performance in a statistically detectable way. Together, these findings reframe SDG achievement as contingent on how development capacities are configured and directed toward sustainability objectives, rather than merely accumulated.

The central policy imperative is not to maximize innovation volume but to govern its direction. Advanced economies should prioritize redirecting mature innovation systems toward decarbonization, circular production, and socially inclusive technological change, given that aggregate innovation intensity no longer drives SDG performance. For developing economies, the window of opportunity to expand innovation capacity while sustainability returns remain positive is real but conditional. Several limitations point toward productive directions for future research. The high inter-correlations among structural regressors constrain the precision of HDI estimates and the interaction term. Future studies employing disaggregated human development indicators, sector-specific innovation measures, and dynamic panel or threshold regression techniques would help clarify the mechanisms and conditions under which the innovation-sustainability paradox materializes across diverse development contexts.

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