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RESEARCH ARTICLE

A Multidimensional Assessment of Country-Level Sustainable Development Goal (SDG) Progress Using Sustainable Trade Metrics

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ABSTRACT

Sustainable development is an important topic based on three fundamental elements—social, economic, and environmental—and provides information about countries' levels of well-being. This study investigates the sustainable trade index and its relationship with sustainable development goals. Accordingly, a multi-stage statistical approach was followed in the study due to the inclusion of different economic, social, and environmental indicators. First, factor analysis was conducted using Principal Component Analysis (PCA) to assess the impact of trade, governance, and environmental indicators on SDG performance. Multiple regression analysis was then used to identify variables that impact sustainable development goals. Cluster analysis then clustered/grouped countries based on their level of development, i.e., their level of economic development. The obtained results offer a more holistic and analytical understanding of the relationship between sustainable development goals and trade systems. The proposed three-stage statistical model is expected to provide useful insights for researchers and policymakers working on sustainable development and trade.

Keywords: Sustainable development goals, Sustainable trade index, PCA, Regression analysis, Cluster analysis

1. Introduction

Sustainable development is an important issue in the global world and is followed with interest by researchers. The Sustainable Development Goals (SDGs) are goals announced by the United Nations in 2015 and cover social, economic and environmental dimensions. The SDGs are evaluated under different subject themes such as poverty reduction, climate action, gender equality, environmental protection, and global institutional cooperation. The study consists of a comprehensive context including seventeen goals and one hundred and sixty-nine targets (United Nations, 2015). The SDGs are fundamentally focused on ensuring people and their living conditions, thus aiming a balance between economic, social, and ecological issues to achieve sustainable development rather than realistically rigid and difficult-to-achieve targets. As Sachs et al. (2019) argue, the SDGs are ground-breaking global development by indicating a shift from sectoral development planning to a holistic and interconnected style.

International trade provides a strategic role and substantial impact on the increasing globalization and sustainability issues. Because trades activities increase productivity levels, stimulates technological transmission, and supports participation in global value chains (Gereffi, 2018). The mentioned matters are closely connected to SDG targets such as decent work and economic growth, industry and innovation, and reduced inequalities. Also, if the trade system is not managed properly, some adverse events could not be prevented. For instance, environmentally harmful production practices will become prevalent, and leads to intensified carbon emissions and social inequalities (OECD, 2020). The importance of this topic is emphasized by the fact that trading systems have both positive and negative impacts on sustainable development. This paradigm is complicated and multifaceted, and therefore, objective analytical tools are needed in this area. In this context, the Sustainable Trade Index (STI) has been proposed to assess the extent to which national trade systems support long-term sustainable development. Developed jointly by the Hinrich Foundation and the IMD World Competitiveness Center since 2022, the STI offers the opportunity to evaluate national economies based on economic, social, and environmental criteria (Hinrich Foundation and IMD, 2024). This multidimensional approach distinguishes the STI from other traditional trade indices that assess competitiveness, trade openness, or export performance.

The relationship between sustainable development and trade has been examined in numerous studies. Trade is not only relevant to sustainable development in the SDG agenda, but also to many other important areas such as sustainable consumption and production, climate action, innovation, and global economic governance. Chen et al. (2025) stated that international trade can affect SDG performance in the domestic and foreign economy and reported that the impact of trade on SDGs depends particularly on institutional capacity and environmental governance.

According to literature different researchers evaluated low-carbon technological developments. For instance, Ioannou et al. (2023) mentioned that energy-intensive sectors present trade-offs in achieving some objectives, chiefly between climate change mitigation and economic or social purposes. The obtained result highlights the efficiency of sustainable trade policy with regard to various development goals. Bisogno et al. (2025) stated that governance quality in the SDG framework, has a substantial influence on SDG performance. For this reason, the SDG present a transition between the SDGs and the global trading system considering countries' trade behavior under sustainability principles. The established reports have shown that countries that are good at strong labor protection and quality governance systems are also good at sustainable trade performance. (Hinrich Foundation and IMD, 2024). Countries with higher STI scores have also been shown to better cope with global challenges such as energy crises, supply chain shocks and climate risks. It is also understood from these statements that STI is a strategically important issue that provides a share in development.

Countries with good STI performance are also understood to be more likely to participate in sustainable and green global value chains. Conversely, countries with poor performance have also been found to struggle to cope with trade challenges. Most studies analyze only their contribution to the targets. However, they fall short of assessing the outcomes of the development goals. This deficiency necessitates further research on this topic. Studies addressing sustainable trade metrics and SDG performance scores will make a significant contribution, especially to developing countries that have difficulty in maintaining economic and ecological balance (Rodrik, 2017).

This study considers this emerging research agenda by examining the intersections between SDGs and sustainable development. It addresses the identified gap by using a multidimensional analytical framework to jointly examine international trade and sustainable development. Due to the large number of variables, the study employed Principal Component Analysis (PCA) to reduce dimensionality, multiple linear regression to measure the impact of key trade and sustainability components on SDG performance, and cluster analysis to identify groups of countries with similar trade-SDG profiles. This analysis explores how STI scores can reflect a country's capacity to achieve SDG outcomes. By integrating advanced statistical techniques with STI and SDG datasets, the study offers new insights into the complex and evolving relationship between international trade and sustainable development and provides a methodological basis for comparison.

The study is structured as follows. Section 2 provides a comprehensive literature review summarizing previous studies and the conceptual background on sustainable development and trade. Section 3 presents the methodological framework of the study, which includes the use of correlation analysis, principal component analysis, multiple linear regression, and cluster analysis. Section 4 provides application of the methods and the obtained results. Finally, Section 5 concludes the study and give some suggestions for future directions.

2. Literature Review

The sustainable development studies are getting more attention from scientists nowadays due to the importance of the subject and the inclusion of various strategic factors. Since the subject concerns different concepts and subjects, analyses should be made at the intersection of different disciplines and the results obtained should be evaluated in a holistic and systematic manner. Since including only economic indicators would lead to other errors, it would be correct to address the issue with more inclusive variables and parameters that are more appropriate to the subject. For instance, considering GDP as the sole factor affecting development is inappropriate, and therefore, comprehensive research is needed by incorporating more explanatory variables into analyses. In particular, researchers have stated that governance and global trade should be examined together to assess whether their impact on sustainability is significant (OECD, 2019). With the official declaration of the United Nations' sustainable development goals, the subject has been concreted on a more solid basis and thus, 17 goal, 169 target and more than 230 indicator definitions have been expressed with a comprehensive content that can be understood more clearly (Adebayo et al., 2025).

The international trade directly contributes to the following themes of SDGs: Decent Work and Economic Growth (SDG 8), Industry, Innovation and Infrastructure (SDG 9), and Reducing Inequalities (SDG 10) (IMD World Competitiveness Center and Hinrich Foundation, 2024). Even though it contributes so much to development, it can also lead to some sustainability challenges. As can be expected, the intensification of commercial activities raises various sustainability issues such as, carbon emissions from production can increase, the environmental balance can be disrupted, and social inequalities within society can become more pronounced (IMD World Competitiveness Center and Hinrich Foundation, 2022).

To better understand the impact of trade on sustainability, Hinrich IMD STI analytical tool was developed. IMD World Competitiveness Center and the Hinrich Foundation together developed the index in order to evaluate the economies of 30 countries across three component: economic capacity, social development, and environmental management (IMD World Competitiveness Center and Hinrich Foundation, 2024).

• The economic base measures trade infrastructure, export diversification, and innovation capabilities.

• The social base related to human capital (education, health), labor principles, and social inclusion processes

• The environmental base evaluates the different subjects such as resource management, greenhouse gasses, and environmental procedures (IMD World Competitiveness Center and Hinrich Foundation, 2024).

The recent studies examine how trade cooperates with sustainable development through institutional and technological context:

1. Trade-offs in Low-Carbon Technologies
   Ioannou et al. (2023) analyze the sustainability implications of carbon capture and utilization (CCU) technologies using a power-chemicals nexus model. Their life-cycle assessment evaluates contributions to multiple SDGs. It can lead to negative impacts such as water scarcity and mineral depletion. This research highlights the complexity of technological transitions.
2. Governance Quality and Sustainable Development

Governance has a momentous role in the Sustainable Development Goals, and the OECD (2019) has also stated that it is a necessary condition for sustainable development. While there are various studies on the subject, one of the most recent is Adebayo et al. (2025), which considered the effectiveness of governance in sustainable development across 48 African countries for the period 2010-2022, using three major structures (economic, social, and environmental). The results indicate that good governance also has a positive impact on the sustainable development goals. Furthermore, according to the 2024 STI, a newly published report, New Zealand, the United Kingdom, and Australia are leading in terms of sustainability. Detailed analyses have shown that these countries are particularly strong in environmental sustainability, and that countries with generally appropriate environmental policies, social protections, and institutional resilience are better at adapting to long-term sustainability in trade. The STI framework was also updated to reflect changing needs. In the 2024 revision, the index introduced a new indicator for Universal Health Coverage (UHC) under the social pillar, in order to show the growing importance of health equity in sustainable trade considerations (IMD World Competitiveness Center and Hinrich Foundation, 2024).

Despite the progress, key research gaps remain:

• As can be seen from the literature, although the STI contains a rich dataset, there are limited studies that examine causal relationships in depth (analyzing STI scores with national SDG performance measures).

• Research on the role of trade in sustainable development often misses SDG context when investigating environmental or social outcomes.

In summary, the literature highlights that trade alone is not sufficient for sustainability. Trade's contribution to the Sustainable Development Goals depends heavily on how trading systems are structured, managed, and regulated. The Hinrich-IMD STI provides a powerful empirical tool to measure this alignment, and emerging studies — particularly those exploring low-carbon technologies and governance — reveal both opportunities and trade-offs. However, deeper integration between trade-index data and national SDG performance remains a vital frontier for future research.

3. Methodology

This study employs a quantitative three stage multivariate method to examine the relationship between countries' STI scores and their performance on selected SDGs.

3.1 Correlation Analysis

Correlation analysis is conducted to measure the strength and direction of linear relationships between STI sub-indices and SDG performance metrics. The Pearson correlation coefficient *(r)* is calculated, which ranges from -1 to +1 and if $r > 0$ specifies a positive association, $r < 0$ shows a negative association and $r = 0$ indicates no linear relationship.

Correlation analysis guides to specify which STI dimensions (economic, social, environmental) are most strongly associated with specific SDG outcomes and offers perceptions into potential synergies or trade-offs.

3.2 Principal Component Analysis

PCA is a multivariate statistical method used to lessen the dimensionality of a dataset while protecting as much variability as possible. It converts the original correlated variables into a smaller set of uncorrelated factors called principal components. Each principal component is a linear combination of the original variables, ordered such that the first component has the maximum variance, the second component has the next highest variance orthogonal to the first, and so on. Principal components possess characteristics that enhance statistical and machine learning models. Specifically, they capture the maximum unique information, remain uncorrelated with each other, and reduce the total number of variables. For PCA, the KMO measure and Bartlett's test are also performed to ensure the data's suitability. Simply put, principal component analysis generates a limited set of well-defined, informative indices for use in your model.

3.3 Multiple Linear Regression

Regression analysis is a statistical method applied to investigate the connection between variables by recognizing a line of best fit through the observed data. Multiple linear regression extends this approach to situations with two or more independent

variables, allowing for the evaluation of their combined effect on a single dependent variable.
The general formula for a multiple linear regression model can be stated as seen in Equation 1:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 \ldots \beta_n x_n + \epsilon \quad (1)$$

where

- y represents the predicted value of the dependent variable, β_0 is the intercept, $\beta_1 x_1 \ldots \beta_n x_n$ are the regression coefficients, and ϵ is the error term.

3.4 Cluster Analysis

Cluster analysis is utilized for searching and segmenting multivariate datasets into groups. It is particularly useful when the existence or number of groups within the data is not known in advance. The primary objective is to identify and describe underlying patterns or structures in the dataset based on the observed variables.
In sustainability research, countries can be grouped according to their STI and SDG profiles to identify clusters of similar performance. Cluster analysis assumes that the dataset consists of units originating from multiple, distinct populations or sub-populations, but these populations are not predefined. Clustering analysis is used to group countries with similar profiles in terms of STI scores and SDG performance. This method identifies homogeneous clusters of countries, allowing for the analysis of patterns and differences across groups.

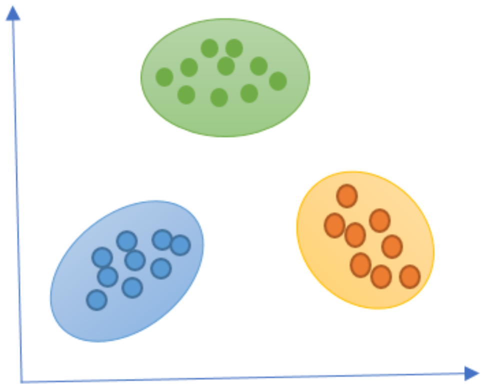

Figure 1. A visual representation of the clustering

According to the Figure 1, it is obvious that the data form three distinct clusters. Within each cluster, data points show high similarity, indicating comparable performance patterns, whereas data points from different clusters display considerable dissimilarity, reflecting different sustainability and trade features.

4. Application of Methods

In this study, the analytical framework is constructed around one dependent variable—the SDG Index—and thirteen independent variables in order to provide economic, social, environmental, demographic, and governance dimensions. All statistical analyses were performed using the Minitab statistical software.
Data for the analysis are drawn from multiple sources and data from 2024 was used in the study as follows:
United Nations Sustainable Development Report 2019 (Sachs et al., 2019), IMD World Competitiveness Center & Hinrich Foundation, (2022; 2024) and governance indicators are obtained from OECD (2019) and additional peer-reviewed sources (Adebayo et al., 2025; Bisogno et al., 2025; Worldbank, 2024) to capture institutional quality, regulatory effectiveness, and social inclusion.

This study employs a cross-country dataset integrating indicators from the STI, the SDG framework, and complementary socioeconomic and environmental variables. The purpose of this dataset is to capture multidimensional aspects of sustainable trade performance and overall development outcomes. All variables included in the analysis serve as inputs to the PCA, regression modelling, and cluster analysis. The variables used in the study are as follows:

- SDG index: It provides as the primary dependent variable in the regression analysis.
- STI: It is a multidimensional index assessing how effectively national trade systems support long-term sustainable development. And social pillar of STI measures institutional quality, labor protections, human capital, social inclusion, and health-related factors within the national trade system. Environmental pillar of STI captures environmental regulations, carbon productivity, pollution levels, biodiversity protection, and resource management. And economic

pillar of STI includes trade infrastructure, export diversification, innovation capacity, and resilience to global value chain shocks.

- GDP per capita (US$): It shows the level of economic development and national income, providing insight into the relationship between prosperity and sustainable development outcomes.
- Population: It measures number of people.
- Trade cost: It evaluates barriers and frictions in international trade, reflecting structural efficiency and integration into global markets.
- Technological innovation: It assesses countries' capacity to generate and adopt new technologies, influencing productivity and competitiveness.
- Life expectancy at birth: It is a key indicator of social well-being and health outcomes, included to capture broader societal development.
- Educational attainment: It gives the level of human capital accumulation, linked to productivity, social progress, and long-term sustainability.
- Air pollution: It provides ecological performance, serving as an important sustainability constraint.
- Government response: It shows governance quality, policy effectiveness, regulatory capacity, and state responsiveness to socioeconomic and environmental challenges.
- Exports of service goods: It gives economic diversification and the structure of trade.

The methodology integrates statistical correlation, regression analysis, and dimension reduction techniques to assess the strength and direction of relationships between STI scores and SDG outcomes. Specifically:

1. Pearson Correlation Analysis identifies linear associations between STI sub-indices and SDG performance metrics.
2. PCA is applied to selected STI-related variables (e.g., Sus.Trade Index, Trade cost, Education attainment, Technological Innovation, Environmental pillar) to reduce multi-collinearity and extract orthogonal components representing the underlying structure of the data. PCA scores are used in subsequent regression models.
3. Multiple Linear Regression Models are employed using the PCA-derived components as independent variables to test their predictive power on SDG outcomes, while controlling for economic and demographic factors.
4. Clustering Analysis groups countries with similar profiles in terms of STI scores and SDG performance. This method identifies homogeneous clusters of countries, allowing for the analysis of patterns and differences across groups.

The data table and its sources are given in Table 1. Russia was removed from the original dataset due to the missing data in the 2024 Sustainable Trade Index. In the study, current 2024 data were analyzed, and in cases where data was missing, the closest year, 2023, was used.

Table 1. 2024 SDI, STI and sub factors data set (Adebayo et al., 2025; IMD World Competitiveness Center & Hinrich Foundation, 2024; Worldbank,2024)

Economy	SDG index	STI	Social pillar	Environmental pillar	Economic pillar	GDP per capita (US$)	Population (people)	Trade cost	Technological innovation	Life expectancy at birth (year)	Education attainment	Air pollution (μg/m³)	Government response	Exports of service goods
New Zealand	78.80	100.00	100.00	100.00	86.00	47536.74	5338.5	87.47	41.13	83.006	67.129	6.49	73.221	1.805
United Kingdom	82.20	97.70	93.70	99.40	87.80	49098.98	69226	79.06	61.75	82.156	88.355	9.84	100.000	53.521
Australia	82.50	87.40	99.60	83.20	75.40	65434.33	27204.82	81.88	54.99	83.579	84.192	8.25	98.801	12.219
Singapore	71.40	85.70	87.00	75.20	92.40	84734.28	6036	100.00	64.17	84.133	65.273	14.01	56.355	33.409
Japan	79.90	81.50	81.90	91.20	72.20	33805.94	123975.4	84.98	57.19	84.82	56.786	12.95	47.322	28.111
South Korea	78.40	81.40	85.40	67.40	92.20	33192.05	51751.08	75.05	100.00	84.024	75.350	25.85	34.373	20.673
Hong Kong (SAR)	74.60	81.40	65.80	79.20	100.00	50029.78	7524.11	86.11	55.21	84.315	70.304	17.77	36.531	17.730
Canada	78.80	80.00	99.80	61.00	81.10	53547.72	41288.61	88.56	43.02	82.847	72.206	6.56	92.806	21.345
Taiwan	74.30	72.30	87.10	61.20	76.70	32443.71	23404.01	79.69	96.10	80.01	66.982	16.24	79.182	11.777
United States	74.40	72.20	69.40	65.30	90.00	81632.25	340111	79.64	55.48	78.203	100.000	7.84	90.647	100.000
Chile	77.80	63.90	65.42	74.45	66.65	16815.78	19764.77	57.57	9.22	79.519	60.448	24.19	96.163	2.258
Thailand	74.70	55.40	57.57	60.28	70.04	7337.194	71668.01	43.56	19.86	79.68	30.657	30.83	74.420	9.719
Philippines	67.50	54.80	37.44	93.01	55.99	3867.672	115843.7	31.55	29.72	72.187	24.588	20.15	99.760	4.783
Vietnam	73.30	54.10	43.83	72.49	68.67	4324.049	100987.7	40.50	19.72	74.58	25.955	20.63	45.484	7.697
Malaysia	69.30	52.70	43.15	71.41	67.26	12570.46	35557.68	58.41	*26.56*	76.26	37.542	16.29	43.086	8.711
China	66.80	50.90	28.18	60.23	89.47	12513.87	1408975	50.22	37.97	78.587	51.101	34.84	16.547	92.488
Mexico	76.50	48.90	34.98	91.04	47.43	13641.61	130861	17.97	10.69	74.832	30.752	15.05	74.420	14.505
Indonesia	74.50	45.30	35.12	73.37	57.02	4942.361	283487.9	30.46	5.27	68.25	26.271	18.07	69.624	7.020

Cambodia	77.10	42.40	24.19	78.35	56.70	2460.351	17638.81	4.28	2.03	69.896	1.073	24.13	35.252	0.620
Peru	83.90	36.00	40.00	55.77	49.36	7932.905	34217.86	25.22	3.95	73.385	31.032	27.18	74.420	1.333
Ecuador	73.40	32.90	43.92	59.36	34.91	6581.574	18135.49	21.50	6.95	77.894	34.029	17.22	78.977	0.608
Laos	62.50	25.00	30.90	78.55	11.39	2004.349	7077.01	8.34	6.08	68.999	3.084	22.59	57.874	0.097
India	64.00	24.00	13.32	43.09	62.30	2500.356	1450936	44.04	9.74	67.744	22.500	48.3	57.874	33.843
Brunei	67.00	22.10	41.32	24.29	49.01	34248.03	462.73	57.79	11.83	74.551	33.751	7.62	9.033	0.000
Bangladesh	64.30	21.30	21.66	58.85	32.23	2621.288	173562.4	12.12	0.21	73.698	13.969	42.28	60.272	1.146
Sri Lanka	67.40	16.80	42.50	58.00	2.37	3341.996	21916.01	29.44	1.00	76.61	28.971	19.99	68.425	0.405
Papua New Guinea	52.00	3.20	0.00	50.15	22.77	2524.633	10576.51	15.72	16.03	65.958	0.000	17	0.000	0.044
Pakistan	57.00	3.70	17.37	56.57	0.00	1460.74	251269.2	25.32	1.59	66.431	1.163	44.31	41.327	0.813
Myanmar	62.11	11.10	12.72	55.54	31.39	1189.842	54500.09	0.00	0.00	67.256	9.673	32.83	18.945	0.246

As given in Table 2, the Pearson correlation analysis was conducted to examine the relationships among sustainability-related variables. The r value is an important clue to understand the relationships between factors. According to the results, the SDG index shows a strong, positive and significant relationship with the variables STI (r = 0.774), social infrastructure (r = 0.744), economic infrastructure (r = 0.634), life expectancy (r = 0.693) and education level (r = 0.665). This points out that countries with higher economic, social, and health indicators tend to perform better in achieving SDGs.

The SDG index shows a moderate strength relationship with environmental factors (r = 0.502) and trade costs (r = 0.521). Environmental performance and trade efficiency contribute to SDG outcomes, but not as strongly as social and economic factors.

There are also some negative correlations between the SDG index and other variables such as air pollution (r = -0.486). This suggests that higher pollution levels lead to lower SDG performance. GDP per capita is positively correlated with most pillars (e.g., economic pillar: r = 0.684) but has a low correlation with population (r = 0.140). This suggests that larger population size does not necessarily translate to higher SDG performance.

Table 2. Correlation analysis

	Sust.Development	Sus.Trade Index	Social pillar	Environmental
Sus.Trade Index	0.774			
	0.000			
Social pillar	0.744	0.912		
	0.000	0.000		
Environmental pi	0.502	0.654	0.469	
	0.006	0.000	0.010	
Economic pillar	0.634	0.870	0.693	0.354
	0.000	0.000	0.000	0.059
GDP per capita	0.471	0.756	0.798	0.266
	0.010	0.000	0.000	0.163
Population	-0.249	-0.161	-0.324	-0.264
	0.194	0.403	0.086	0.167
Trade cost	0.521	0.847	0.875	0.271
	0.004	0.000	0.000	0.155
Techn. Innovatio	0.430	0.778	0.766	0.313
	0.020	0.000	0.000	0.099
Life expectancy	0.693	0.861	0.896	0.398
	0.000	0.000	0.000	0.033
Education attain	0.665	0.866	0.879	0.341
	0.000	0.000	0.000	0.070
Air pollution	-0.486	-0.583	-0.642	-0.387
	0.007	0.001	0.000	0.038
Goverment respon	0.575	0.478	0.529	0.470
	0.001	0.009	0.003	0.010
Exports of servi	0.149	0.380	0.234	0.079
	0.439	0.042	0.222	0.686

	Economic pillar	GDP per capita	Population	Trade cost
GDP per capita	0.684			
	0.000			
Population	0.140	-0.168		
	0.470	0.383		
Trade cost	0.797	0.859	-0.041	
	0.000	0.000	0.831	
Techn. Innovatio	0.737	0.704	-0.076	0.811
	0.000	0.000	0.697	0.000
Life expectancy	0.730	0.727	-0.207	0.843
	0.000	0.000	0.282	0.000
Education attain	0.798	0.859	-0.049	0.890
	0.000	0.000	0.802	0.000

	Techn. Innovatio	Life expectancy	Education attain	Air pollution
Air pollution	-0.382	-0.634	0.537	-0.538
	0.041	0.000	0.003	0.003
Goverment respon	0.209	0.298	-0.168	0.277
	0.278	0.116	0.383	0.146
Exports of servi	0.555	0.496	0.574	0.436
	0.002	0.006	0.001	0.018
	Techn. Innovatio	**Life expectancy**	**Education attain**	**Air pollution**
Life expectancy	0.734			
	0.000			
Education attain	0.792	0.855		
	0.000	0.000		
Air pollution	-0.420	-0.525	-0.567	
	0.023	0.003	0.001	
Goverment respon	0.163	0.354	0.461	-0.286
	0.399	0.060	0.012	0.132
Exports of servi	0.439	0.323	0.572	-0.084
	0.017	0.087	0.001	0.666

An initial multiple regression model was estimated using all 13 original variables related to sustainable trade, socioeconomic structure, governance, and environmental performance (Table 3). Although the model showed a high R^2 (85%), nearly all predictors were statistically insignificant and VIF values exceeded 5 indicating severe multicollinearity. Therefore, PCA was applied to reduce dimensionality, eliminate multicollinearity, and extract uncorrelated components representing the underlying structure of the dataset. The subsequent PCA-based regression provided a more stable model with interpretable coefficients and improved predictive validity.

Table 3. Initial regression analysis

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	13	1448.44	111.419	6.54	0.000
Sus.Trade Index	1	28.67	28.674	1.68	0.214
Social pillar	1	9.49	9.492	0.56	0.467
Environmental pillar	1	28.52	28.518	1.67	0.215
Economic pillar	1	15.94	15.938	0.94	0.349
GDP per capita (US$)	1	7.71	7.715	0.45	0.511
Population	1	0.00	0.001	0.00	0.995
Trade cost	1	112.27	112.275	6.59	0.021
Techn. Innovation	1	66.86	66.858	3.92	0.066
Life expectancy at birth	1	0.69	0.694	0.04	0.843
Education attainment	1	29.73	29.733	1.75	0.206
Air pollution	1	0.08	0.081	0.00	0.946
Goverment response	1	3.90	3.899	0.23	0.639
Exports of service goods	1	3.54	3.541	0.21	0.655
Error	15	255.57	17.038		
Total	28	1704.01			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
4.12774	85.00%	72.00%	0.00%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	111.0	51.1	2.17	0.046	
Sus.Trade Index	1.61	1.24	1.30	0.214	2070.93
Social pillar	-0.407	0.546	-0.75	0.467	433.05
Environmental pillar	-0.729	0.564	-1.29	0.215	152.42
Economic pillar	-0.544	0.562	-0.97	0.349	401.16
GDP per capita (US$)	-0.000057	0.000085	-0.67	0.511	7.65
Population	0.000000	0.000005	0.01	0.995	5.26
Trade cost	-0.264	0.103	-2.57	0.021	15.85
Techn. Innovation	-0.1191	0.0601	-1.98	0.066	4.88
Life expectancy at birth	-0.076	0.379	-0.20	0.843	8.74
Education attainment	0.161	0.122	1.32	0.206	20.00
Air pollution	0.009	0.126	0.07	0.946	3.29
Goverment response	-0.0268	0.0561	-0.48	0.639	4.12
Exports of service goods	-0.0344	0.0754	-0.46	0.655	6.12

Regression Equation

Sust.Development Goal Index = 111.0 + 1.61 Sus.Trade Index - 0.407 Social pillar
- 0.729 Environmental pillar - 0.544 Economic pillar

```
                           - 0.000057 GDP per capita (US$) + 0.000000 Population
                           - 0.264 Trade cost - 0.1191 Techn. Innovation
                           - 0.076 Life expectancy at birth
+ 0.161 Education attainment
                           + 0.009 Air pollution - 0.0268 Goverment response
                           - 0.0344 Exports of service goods
```

The results confirm multicollinearity among several indicators, justifying the subsequent use of PCA to reduce dimensionality and extract independent factors for further regression and cluster analysis.
PCA was carried out after the Bartlett test and the KMO measure confirmed that the data were appropriate for this analysis. The KMO measure (0.70) and Bartlett's test ($\chi^2 = 534.84$, $p < 0.001$) confirmed that the data were suitable for factor analysis.

Table 4. Principal Component Analysis

Eigenanalysis of the Correlation Matrix

Eigenvalue	7.6818	2.0228	1.0801	0.6609	0.5719	0.2818	0.2094	0.1878	0.1741
0.0481									
Proportion	0.591	0.156	0.083	0.051	0.044	0.022	0.016	0.014	0.013
0.004									
Cumulative	0.591	0.747	0.830	0.880	0.924	0.946	0.962	0.977	0.990
0.994									
Eigenvalue	0.0435	0.0376	0.0003						
Proportion	0.003	0.003	0.000						
Cumulative	0.997	1.000	1.000						

Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8
Sus.Trade Index	0.346	-0.042	0.151	-0.229	0.048	-0.171	-0.086	-0.047
Social pillar	0.340	-0.143	-0.022	0.083	0.238	0.008	0.063	0.003
Environmental pillar	0.180	-0.269	0.550	-0.543	-0.312	0.144	0.191	-0.189
Economic pillar	0.303	0.223	0.018	-0.281	0.041	-0.472	-0.376	-0.009
GDP per capita (US$)	0.316	0.046	-0.208	0.260	-0.220	0.128	0.139	-0.688
Population	-0.060	0.629	0.288	0.017	0.033	-0.266	-0.081	-0.013
Trade cost	0.333	0.101	-0.183	0.042	0.165	-0.129	-0.010	-0.307
Techn. Innovation	0.302	0.115	-0.183	-0.252	0.172	0.658	-0.438	0.220
Life expectancy at birth	0.325	-0.031	-0.078	-0.062	0.286	-0.149	0.648	0.388
Education attainment	0.344	0.097	-0.005	0.215	0.027	0.063	0.063	0.149
Air pollution	-0.235	0.317	0.228	-0.172	0.620	0.288	0.238	-0.348
Goverment response	0.164	-0.229	0.629	0.573	0.211	0.051	-0.246	0.048
Exports of service goods	0.169	0.520	0.162	0.162	-0.473	0.281	0.229	0.220

Variable	PC9	PC10	PC11	PC12	PC13
Sus.Trade Index	-0.078	-0.020	0.100	0.255	-0.825
Social pillar	0.187	-0.021	0.171	0.771	0.370
Environmental pillar	0.168	0.076	-0.122	-0.094	0.222
Economic pillar	-0.518	-0.057	0.034	-0.095	0.362
GDP per capita (US$)	-0.121	-0.439	-0.139	-0.056	-0.006
Population	0.550	-0.294	-0.215	0.054	0.003
Trade cost	0.397	0.546	0.349	-0.356	0.025
Techn. Innovation	0.143	-0.226	-0.012	-0.157	0.007
Life expectancy at birth	-0.003	-0.332	0.039	-0.311	0.016
Education attainment	-0.103	0.443	-0.765	0.048	-0.026
Air pollution	-0.311	0.127	0.002	0.058	-0.009
Goverment response	-0.071	-0.105	0.136	-0.229	0.016
Exports of service goods	-0.232	0.168	0.390	0.105	0.004

To address the multicollinearity issue among the independent variables in this study, PCA was applied to the statistical model. In order to identify the principal components, the correlation matrix is utilized and with regards to the eigenvalues, ten components were obtained from the analysis. According to the analysis in Table 4, the first three components (PC1, PC2, and PC3) represents 83 percent of the total variance in the model (PC1: 59.1%, PC2: 15.6%, PC3: 8.3%). This means that these three principal components reflect most of the information contained in the original variables. Therefore, these components were used in successive analysis phases since they are enough to represent the dataset in the original problem and reduce multicollinearity, a significant problem.
The component loadings provided insight into the interpretation of each principal component. PC1 exhibited high positive loadings on the Sustainable Trade Index, Social Pillar, Education, Life Expectancy, and GDP per capita, suggesting that it represents a general socioeconomic and development factor. PC2 had strong loadings from Population and Exports of Service Goods, reflecting a demographic and economic scale dimension. PC3 was primarily influenced by the Environmental Pillar

and Government Response, indicating a governance and environmental factor. These components were subsequently used as predictors in regression analyses as given in Equation 2 and as input variables for clustering, enabling a more robust examination of patterns across countries while reducing redundancy in the data.

$$Sust.Development\ Goal\ Index = \beta 0 + \beta 1 * PC1 + \beta 2 * PC2 + \beta 3 * PC3 + \varepsilon \tag{2}$$

Regression Analysis Using Principal Components

Following the PCA, a multiple linear regression was conducted to examine the effect of the principal components (PC1, PC2, PC3) on the SDG index. The first three principal components, which explained the majority of variance in the original dataset, were used as predictors. According to residual plots as given in Figure 2, we can obtained the following results:

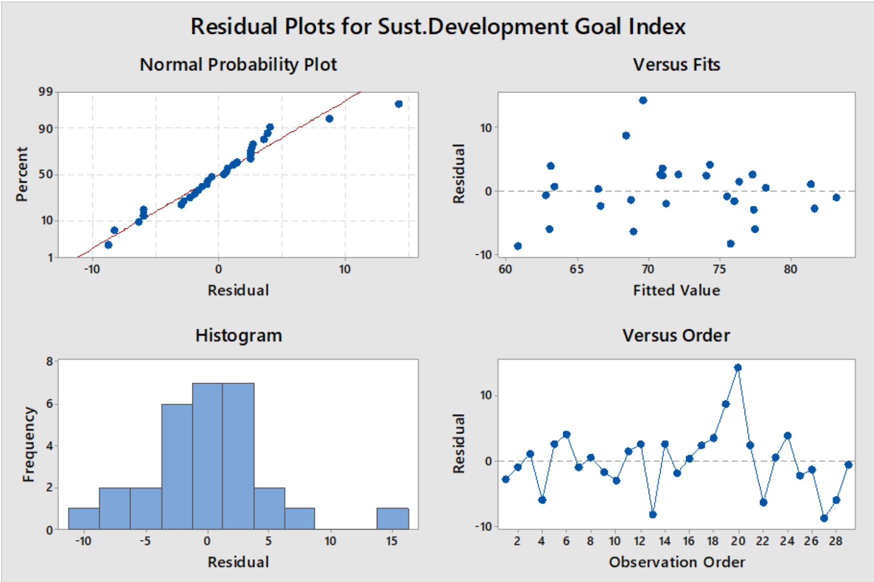

Figure 2. Residual plots for regression analysis

- Firstly, according to normal probability plot (Q-Q plot), the residuals are almost normally distributed since points are very close to the red line (mostly around the mean. The overall distribution is appropriate for normality.
- Secondly, according to residuals vs. fitted values, residuals are randomly distributed around the fitted values and there is no any specific pattern. So, it supports the assumption of homoscedasticity.
- Thirdly, histogram resembles a normal distribution, with no apparent skewness to the left or right. The frequency distribution of residuals is approximately symmetric and unimodal.
- Fourthly, according to the residuals vs. observation order graph, residuals are randomly distributed over the observation order. And there is no serial correlation, temporal dependency, or systematic model error is observed.

As seen from the analysis result, the residuals meet the assumptions of normality, constant variance (homoscedasticity), and independence in order to realize regression model.

Table 5. Regression analysis of PCA components

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	1050.49	350.16	13.40	0.000
PC1	1	850.54	850.54	32.54	0.000
PC2	1	91.81	91.81	3.51	0.063
PC3	1	108.14	108.14	4.14	0.051
Error	25	653.53	26.14		
Total	28	1704.01			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
5.11283	63.65%	59.05%	50.56%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	71.945	0.949	75.78	0.000	
PC1	1.989	0.349	5.70	0.000	1.00
PC2	-1.273	0.679	-1.87	0.063	1.00

```
PC3          1.891    0.930     2.03    0.051  1.00

Regression Equation
Sust.Development Goal Index = 71.945 + 1.989 PC1 - 1.273 PC2 + 1.891 PC3
```

The regression model was significant overall *($F = 13.40$, $p < 0.001$)*, with an R^2 of *0.636* and an *adjusted* R^2 of *0.590*, indicating that approximately *60%* of the variability in the SDG Index is accounted for by the three principal components. The regression equation is given in Equation 3 as follows:

$$SDG\ index = 71.945 + 1.989 * PC1 - 1.273 * PC2 + 1.891 * PC3 \quad (3)$$

PC1 is positively and significantly associated with the SDG Index. It means that higher scores on the first principal component, representing a combination of socioeconomic and trade factors, are linked to higher SDG Index values. PC3 is positively associated with the SDG Index with borderline significance, reflecting the influence of environmental and governance factors on the SDG Index. According to VIFs values, there is no multicollinearity issues among predictors. Residual diagnostics showed that the model fit the data reasonably well.
Overall, PC1 emerges as the strongest predictor, followed by PC3, while PC2 has a weaker effect. These principal components can also be used in subsequent cluster analysis to identify groups of countries with similar SDG-related characteristics. Table 5 shows the regression results of the PCA components.

In order to determine ideal cluster number, the silhouette analysis have been applied and the obtained results are given in the Table 6:

Table 6. Silhouette scores

Number of Clusters	Silhouette Score
2	0.5185
3	0.5464
4	0.4457
5	0.4525
6	0.3790

The suitability of 3 clusters was justified based on the silhouette score, dendrogram structure, and similar studies in the literature. According to Table 6, three clusters show highest silhouette score so it means clusters are well-separated and statistically meaningful.

According to the cluster analysis results presents in Table 7, hierarchical cluster analysis depends on the first three principal components (PC1, PC2, PC3) and it means three distinct country groups. While the first cluster represents economically advanced nations with strong trade performance, Cluster 2 includes countries with moderate economic outcomes but strong social and environmental performance. Besides, Cluster 3 represents weaker countries in terms of economic and environmental measures. The distances between cluster centroids highlight the heterogeneity of SDG performance across countries. This categorization ensures a framework for strategic policies and aimed SDG actions.

Table 7. Cluster Analysis

Euclidean Distance, Ward Linkage

Step	Number of clusters	Similarity level	Distance level	Clusters joined		New cluster	Number of obs. in new cluster
1	28	94.772	0.4614	7	9	7	2
2	27	94.179	0.5136	1	3	1	2
3	26	93.453	0.5777	12	14	12	2
4	25	92.510	0.6609	13	17	13	2
5	24	92.456	0.6657	18	20	18	2
6	23	92.305	0.6790	19	26	19	2
7	22	92.150	0.6927	5	8	5	2
8	21	90.453	0.8424	28	29	28	2
9	20	89.722	0.9069	18	21	18	3
10	19	89.582	0.9193	12	15	12	3
11	18	89.008	0.9699	6	7	6	3
12	17	88.673	0.9995	19	22	19	3
13	16	83.490	1.4568	4	6	4	4
14	15	82.822	1.5157	4	5	4	6
15	14	82.158	1.5744	25	28	25	3
16	13	78.853	1.8660	11	13	11	3

```
  17        12       78.548    1.8929   1      2        1        3
  18        11       75.456    2.1658  18     19       18        6
  19        10       74.456    2.2540  25     27       25        4
  20         9       64.992    3.0891  16     23       16        2
  21         8       60.933    3.4473   4     10        4        7
  22         7       60.886    3.4514  11     12       11        6
  23         6       41.664    5.1476  24     25       24        5
  24         5       41.530    5.1594   1      4        1       10
  25         4       32.628    5.9449  11     18       11       12
  26         3      -22.489   10.8085  16     24       16        7
  27         2      -49.140   13.1601  11     16       11       19
  28         1     -401.283   44.2331   1     11        1       29
Final Partition
Number of clusters: 3
                                        Average   Maximum
                               Within  distance  distance
            Number of     cluster sum      from      from
          observations     of squares  centroid  centroid
Cluster1            10        17.1279   1.21386   2.16213
Cluster2            12        18.9399   1.16624   1.95288
Cluster3             7        57.4460   2.67375   4.70685

Cluster Centroids
Variable  Cluster1  Cluster2  Cluster3  Grand centroid
PC1        3.36872  -1.17235  -2.80272       0.0000000
PC2       -0.00290  -0.74656   1.28395      -0.0000000
PC3       -0.21439   0.48720  -0.52892       0.0000000

Distances Between Cluster Centroids
          Cluster1  Cluster2  Cluster3
Cluster1   0.00000   4.65473   6.31202
Cluster2   4.65473   0.00000   2.79528
Cluster3   6.31202   2.79528   0.00000
```

Figure 3 shows the dendogram of the cluster analysis.

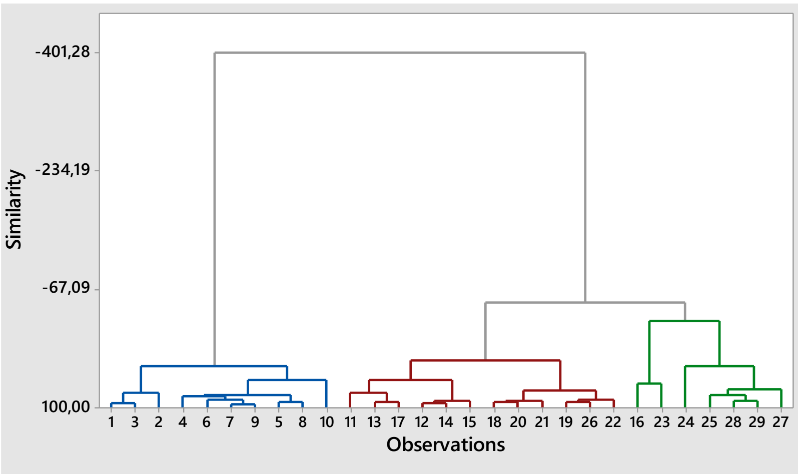

Figure 3. Dendogram of the cluster analysis

When we discussed the cluster analysis results we obtained the following results: Cluster 1 provides high economic/trade performance and it includes economically developed nations with high trade volumes, such as Germany, Japan, USA, or South Korea. These countries perform well on SDG dimensions related to economic growth and trade but may have average performance on environmental or social measures. Cluster 2 ensures social & environmental strengths and it comprises moderate economic performance and covers northern European countries like Sweden, Denmark and Norway. This cluster represents countries that achieve high SDG performance primarily through social inclusion, education, and environmental sustainability, even if economic/trade metrics are moderate. Lastly, Cluster 3 presents lower economic & environmental performance and it includes weak economic and environmental indicators. Some developing nations or which facing economic and environmental challenges, such as some African or South Asian countries (e.g., India, or Pakistan). These countries have relatively lower overall SDG performance.

5. Conclusion and Future Directions

Sustainable development goals (SDGs) are one of the top themes that have attracted the attention of the entire world and funded research. As a result, countries are able to lay down their long-term roadmaps through investment plans that are in line with their development goals.

This study has been a comprehensive performance evaluation of the SDGs in different countries by employing a three-stage statistical framework combining PCA, multiple linear regression, and hierarchical cluster analysis. PCA helped compress the multidimensional dataset to the three most significant principal components. The regression analysis revealed that these three components accounted for about 60% of the variation in the SDG Index with PC1 that represents socioeconomic and trade-related factors being the strongest positive predictor. Subsequently, a cluster analysis was employed to group countries based on the similarities in their performance patterns across each SDG. The results of the cluster analysis reveal how different structural, economic, social, and environmental factors affect the performance of the SDGs, thus demonstrating the significance of the multidimensional approach in assessing sustainable development. This study employs PCA to alleviate the problem of multicollinearity and to simplify the complex datasets without losing much information, thus yielding a more reliable regression model. Also, cluster analysis facilitates the categorization of countries according to similar development profiles with the aim of identifying common and comparative policy objectives.

Concerning the limitations of the research, the possible bidirectional and endogenous relationship between SDG performance and STI components was not taken into account. As STI components may both influence and be influenced by SDG performance, the omission of this factor may constrain the explanation of the regression results. It is suggested that future researchers use two-stage least squares (2SLS), generalized method of moments (GMM), or panel data methods that account for endogeneity.

Upcoming research can incorporate additional variables and evaluate countries' SDG performance in different periods through time series or panel data analysis. The components derived from PCA could also be examined by combining them with high-prediction methods (e.g., random forests, gradient boosting, or neural networks) within machine learning frameworks.

Acknowledgment

There is no conflict of interest

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