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Sustainable Entrepreneurship and Innovation: A Catalyst for the Transition Towards a Green and Blue Economy

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Abstract

This study examines how sustainable entrepreneurship, innovation capacity, governance quality, and environmental performance interact across countries undergoing green and blue economy transitions. Addressing a gap in cross-country work that jointly considers environmental, institutional, and financial indicators, we integrate five internationally recognized sources the Green Growth Index, Ocean Health Index, Global Innovation Index, Corruption Perceptions Index, and national venture-capital investment. Using a quantitative, cross-sectional design, we apply principal component analysis (PCA) and K-means clustering to a sample of 31 developed and emerging economies to uncover latent performance dimensions and country regimes.

Two principal components explain over 82% of total variance. PC1 reflects a Development–Governance–Innovation axis, loading positively on venture capital depth, governance quality (cleaner public sectors), and innovation capacity; PC2 captures an Environmental Sustainability axis, dominated by ocean health with a moderate contribution from green growth. Countries such as Sweden, Switzerland, and the United Kingdom perform strongly on both axes, whereas several emerging economies (e.g., Morocco, India, Kenya) display potential but face institutional and financial constraints. Clustering reveals three regimes: high-performing developed economies, emerging economies with mixed performance, and a singleton outlier (Singapore) combining strong innovation/finance with comparatively weaker ocean outcomes.

Findings underscore the need for integrated strategies that align institutional credibility, innovation systems, and green finance to foster sustainable entrepreneurship and accelerate transitions toward resilient green and blue economies.

Keywords: Sustainable entrepreneurship; Green economy; Blue economy; Innovation systems; Governance; Venture capital; Principal component analysis

1. Introduction

Global economic systems are reorienting toward sustainability in response to climate risk, accelerating technological change, and social demands for inclusive growth. Sustainable entrepreneurship the pursuit of opportunities generating economic, social, and environmental value has emerged as a central mechanism for aligning competitiveness with stewardship (Hall, Daneke, & Lenox, 2010; Schaltegger, Hansen, & Lüdeke-Freund, 2016). This paradigm extends the triple bottom line people, planet, profit beyond firm-level responsibility to the architecture of innovation ecosystems (Elkington, 1997).

Alongside the green economy's emphasis on low-carbon growth and resource efficiency, the blue economy highlights sustainable use of ocean and coastal resources to support development, employment, and ecological resilience (UNDP, 2023; White, Rahill, Gough, & Spurgeon, 2021). Together, these domains offer complementary pathways to the SDGs, notably SDG 8 (decent work), SDG 9 (industry, innovation, infrastructure), and SDG 14 (life below water). Realizing this integrated vision requires more than technology: institutional quality and governance credibility condition investment horizons, de-risk private capital, and enable long-lived innovation programs (Aghion, Dechezleprêtre, Hémous, Martin, & Van Reenen, 2016; Mazzucato, 2018).

Research on entrepreneurial ecosystems and national innovation systems shows that innovation thrives where regulatory stability, finance, human capital, and networks co-evolve (Isenberg, 2010; Stam, 2015). In green/blue sectors, patient risk capital and coherent industrial policy are particularly salient for scaling capital-intensive clean technologies (OECD, 2016; van den Heuvel & Popp, 2022; Yang, 2022). Yet cross-country empirical syntheses that jointly integrate environmental indicators (e.g., Green Growth Index, Ocean Health Index) with innovation and governance remain sparse (Teh & Sumaila, 2013; Dutta, Lanvin, & Wunsch-Vincent, 2024). Moreover, the literature increasingly recognizes that venture capital not only funds emerging clean technologies but also shapes the direction of innovation, while corruption and weak governance depress investment and green-innovation payoffs (Lin, 2022; Wen, 2023; Mauro, 1995).

To address these gaps, this study constructs a multidimensional, comparative framework linking environmental, institutional, innovation, and finance indicators. We employ PCA to harmonize scales and reveal latent structure (Abdi & Williams, 2010), then use K-means to classify countries into interpretable regimes. Our approach contributes by integrating green and blue metrics within a single statistical design;clarifying the separation between a development-innovation-governance axis and an environmental axis; and translating these insights into policy-relevant clusters that can inform sequencing of reforms and finance. For governance-green-innovation linkages, we rely on peer-reviewed international evidence (Makpotche, Bouslah, & M'Zali, 2024), replacing earlier unverifiable attributions.

2. Theoretical Background

2.1 Sustainable Entrepreneurship and Innovation in the Green-Blue Economy

Sustainable entrepreneurship is widely recognized as the deliberate coupling of opportunity recognition with social and environmental value creation, embedding ecological stewardship alongside financial performance within firm strategy and business models (Hall, Daneke, & Lenox, 2010; Schaltegger, Hansen, & Lüdeke-Freund, 2016). In coastal and marine contexts, the blue economy extends this logic by linking ocean natural capital and marine ecosystem resilience to enterprise development in sectors such as fisheries, aquaculture, marine biotechnology, coastal tourism, and renewable ocean energy (Teh & Sumaila, 2013; Silver et al., 2015; OECD, 2016). Recent scholarship emphasizes the mutually reinforcing roles of digitalization, circularity, and sustainability-oriented business models as drivers of green/blue innovation trajectories, underscoring the need to analyze entrepreneurship through an integrated green–blue lens (Schaltegger et al., 2016).

2.2 Governance, Innovation Ecosystems, and Entrepreneurial Finance

Entrepreneurial-ecosystem research highlights how institutions, finance, human capital, infrastructure, and networks co-evolve to support venture formation and scaling (Isenberg, 2010; Stam, 2015). Within sustainability transitions, governance quality through regulatory certainty, transparency, and control of corruption shapes investment risk and the credibility of long-term environmental commitments (Kaufmann, Kraay, & Mastruzzi, 2011). National innovation systems and absorptive capacities help generate, diffuse, and adapt green and blue technologies (Jacobsson & Bergek, 2011; Dutta, Lanvin, & Wunsch-Vincent, 2024). Venture capital (VC) provides risk capital to scale early-stage clean-technology solutions but remains sensitive to policy signals, mission-oriented programs, and the quality of local innovation infrastructure (Mason & Brown, 2014; Gaddy, Sivaram, & O'Sullivan, 2018; Nanda, Younge, & Fleming, 2015). Empirically, higher perceived corruption is associated with weaker green-innovation outcomes (Wen, 2023), while credible governance complements innovation capacity, translating sustainability ambitions into measurable performance improvements (Ambec et al., 2013; Makpotche, Bouslah, & M'Zali, 2024).

2.3 Complex Adaptive Systems (CAS) and Sustainability Transitions

Sustainability transitions unfold within complex adaptive systems comprising interacting agents entrepreneurs, investors, regulators, communities, and ecosystems whose non-linear interactions yield emergent outcomes (Holland, 2014; Geels, 2002; Markard, Raven, & Truffer, 2012). This perspective clarifies heterogeneous national pathways, where path dependence, institutional lock-in, and co-evolution across policy, technology, and markets generate distinct performance "regimes" (Stirling, 2011; Jacobsson & Bergek, 2011). Governance quality and financial signals (e.g., carbon pricing, environmental standards) can redirect innovative effort and accelerate clean-technology diffusion, whereas weak institutions slow transition dynamics (Aghion et al., 2016; Kaufmann et al., 2011).

2.4 Blue Economy and Sustainability Performance

The blue economy emphasizes the sustainable use of ocean and coastal resources for inclusive growth and employment while safeguarding marine ecosystem health and advancing SDG 14 (UNDP, 2023; OECD, 2016). The Ocean Health Index demonstrates that healthier marine ecosystems underpin provisioning, regulating, and cultural services critical to socio-economic stability (Halpern et al., 2012). Empirical evidence on blue natural capital indicates that coral reefs, mangroves, and seagrass meadows deliver risk-reduction and income co-benefits buffering hazards, enhancing fisheries, and supporting resilient tourism thereby linking ecological condition to socio-economic outcomes (White et al., 2021). Policy instruments such as marine spatial planning (MSP), integrated ocean governance, and innovative financing mechanisms (e.g., blue bonds) align investment with conservation and sustainable use (Ehler & Douvere, 2009; World Bank, 2018). Cross-country syntheses jointly considering marine ecosystem condition, governance quality, innovation capacity, and entrepreneurial finance remain limited, motivating the integrative approach of this study.

2.5 Multivariate Syntheses of Sustainability Indicators (Conceptual Overview)

Comparative sustainability research frequently employs multivariate analysis to reveal latent structures among heterogeneous indicators (Jolliffe & Cadima, 2016; Abdi & Williams, 2010). Principal component and related factor-analytic techniques reduce dimensionality after harmonizing indicator direction and scale (Ringnér, 2008; Jackson, 1991); orthogonal rotations such as varimax enhance interpretability by concentrating variable salience on distinct components (Kaiser, 1958). Robust formulations (e.g., ROBPCA) mitigate sensitivity to anomalous values typical of cross-country datasets (Hubert, Rousseeuw, & Vanden Branden, 2005), while complementary manifolds such as t-SNE aid visualization (van der Maaten & Hinton, 2008). When component scores are used to explore group structure, cluster-validity indices (e.g., silhouette, gap statistic) assess stability and separation (Rousseeuw, 1987; Tibshirani, Walther, & Hastie, 2001; Halkidi, Batistakis, & Vazirgiannis, 2001).

2.6 Green Venture Capital and Innovation Dynamics

Venture capital plays a pivotal role in scaling sustainability-oriented technologies whose risk and capital intensity often exceed the tolerance of traditional debt finance (Nanda et al., 2015; Gaddy et al., 2018). Credible carbon-pricing regimes, mission-oriented innovation programs, and regulatory certainty mobilize private investment and steer inventive effort toward cleaner technological trajectories (Aghion et al., 2016; Mazzucato, 2018). Clean-tech ventures face longer development cycles and greater technological uncertainty, producing finance-governance complementarities whereby innovation capacity and institutional quality shape the supply and returns of green VC (Costantini, Crespi, & Palma, 2017; Kaufmann et al., 2011). These dynamics imply that differences in innovation systems and governance generate distinct VC landscapes and diffusion pathways for sustainable technologies across countries.

2.7 Governance, Corruption, and Sustainability Transitions

Institutional quality shapes the efficiency of innovation systems and the effectiveness of environmental policy. Foundational macroeconomic evidence links corruption to lower growth and misallocation (Mauro, 1995), while recent analyses show that corruption suppresses green innovation and weakens clean-investment signals (Wen, 2023). Conversely, countries that combine strong governance with robust innovation systems translate environmental ambitions into measurable performance gains through directed technical change and cumulative capability building (Ambec et al., 2013; Aghion et al., 2016; Jacobsson & Bergek, 2011). In emerging economies, reforms enhancing transparency and regulatory capacity supported by targeted green-finance instruments can accelerate sustainability transitions, though outcomes remain path-dependent and heterogeneous.

3. Methodological Approach

This study adopts a quantitative, cross-sectional research design based on secondary data. A quantitative approach is appropriate because the research seeks to measure and compare objective indicators of sustainable entrepreneurship, innovation, governance and environmental performance across countries. The cross-sectional design enables comparisons at a single point in time, which is suitable for identifying structural patterns and correlations between the variables of interest. By leveraging existing international indices and applying multivariate statistical techniques, the study aims to distil complex, multidimensional information into a small number of interpretable components that support evidence-based policy recommendations.

A) Data collection

Five internationally recognised indices serve as the primary data sources for assessing sustainable entrepreneurship, each capturing a distinct but complementary dimension. The Green Growth Index (GGI) measures progress toward environmentally sustainable and inclusive growth, with scores ranging from 1 to 100, where values below 40 indicate low performance and values above 80 reflect very high performance; 2023/24 data were obtained from the Global Green Growth Institute's online portal. Complementing this, the Ocean Health Index (OHI) evaluates the ecological condition of marine ecosystems, providing annual scores for 220 coastal countries and territories on a 0–100 scale, with consistent methodology ensuring temporal comparability. Governance quality, another critical aspect of sustainable entrepreneurship, is captured by the Corruption Perceptions Index (CPI) from Transparency International, which ranks 180 countries based on perceived public sector corruption, where higher scores denote cleaner governance; the 2024 CPI scores were used. The Global Innovation Index (GII) further reflects countries' capacity to innovate, ranking 133 economies based on 2022–2023 data to indicate national innovation performance. Finally, Venture Capital (VC) investment serves as a proxy for entrepreneurial finance and innovation dynamism, measured as total capital invested (in millions of USD) during 2024, according to Dealroom's curated country-level heatmap. Together, these five indices provide a multidimensional view of the environmental, institutional, innovative, and financial factors that underpin sustainable entrepreneurship globally

B) Sample selection

The study focuses on 31 countries representing a balance of developed and emerging economies across multiple regions. Countries were included if data for all five indicators were available for the most recent year and if they collectively illustrated variation in innovation, governance and environmental performance. One country with incomplete data was removed to ensure comparability and analytical integrity. A list of the countries and their data availability is provided in an appendix.

C) Data extraction and instruments

Data were downloaded directly from the official websites of the indices or their affiliated portals. The GGI, OHI, CPI and GII datasets are publicly accessible, while VC data were obtained through a licensed Dealroom dashboard. The extraction process recorded the year of each observation to ensure alignment across indices. No primary instruments or surveys were used; instead, existing validated indices served as measurement tools.

D) Data preprocessing and analysis

Before conducting the Principal Component Analysis, all variables were carefully defined and preprocessed to ensure comparability and consistency across measures. The Green Growth Index captures a country's environmental sustainability and green-oriented economic progress, where higher values indicate stronger performance. The Ocean Health Score reflects the ecological health of marine ecosystems, with higher scores denoting healthier oceans. The Venture Capital amount represents the total venture capital investment and serves as a proxy for entrepreneurial activity; higher values imply more active investment. The Corruption Perceptions Index assesses perceived levels of corruption, with higher scores indicating cleaner governance. The Global Innovation Index is reported as a ranking, with lower values indicating stronger national innovation capacity. To align the directionality of this rank with the other positively oriented variables, ranks were reversed using the transformation $R_{ij}^{rev} = \left(R_j^{max} + 1\right) - R_{ij}$, ensuring that higher values consistently represent better performance across all indicators.

Table1**:** Description and Preprocessing of Variables for PCA

Variable	Type	Description	Treatment for PCA
Green Growth Index	Score (0–100)	Captures a country's environmental sustainability and green-aligned economic growth. Higher values indicate stronger performance.	Used as-is; higher values indicate better performance.
Ocean Health Score	Score (0–100)	Evaluates the ecological health of a country's ocean ecosystems. Higher scores reflect healthier oceans.	Used as-is; higher values indicate better performance.
Venture Capital (VC) Amount (USD)	Numeric (millions USD)	Represents the total venture capital investment in a country, serving as a proxy for entrepreneurial activity. Higher values indicate more active VC investment.	Used as-is; higher values indicate better performance.
Corruption Perceptions Index	Score (0–100)	Measures perceived levels of corruption, with higher values reflecting lower corruption.	Used as-is; higher values indicate better performance.
Global Innovation Index Rank	Rank (integer, lower = better)	Assesses overall national innovation capacity; lower ranks correspond to more innovative countries.	Directionality reversed to align with other scores: $R_{ij}^{rev} = (R_j^{max} + 1) - R_{ij}$, so that higher values indicate better performance.

The next step in preparing the dataset involves addressing missing values through mean imputation. For each numeric variable x_j, missing entries x_{ij} were replaced with the mean of the observed values for that variable, such that

$$\bar{x}_{ij} = \begin{cases} x_{ij}, & \text{if } x_{ij} \text{ is observed} \\ \bar{x}_j = \dfrac{1}{n_j} \sum\limits_{i \in observed} x_{ij}, & if\ x_{ij} \text{ is missing} \end{cases}$$

Where $n_j$is the number of non-missing entries for variable j. All variables were then standardised to eliminate scale disparities, given PCA's sensitivity to differing magnitudes. Standardisation was performed using z-scores, computed as

$$Z_{ij} = \frac{\bar{x}_{ij} - \mu_j}{\sigma_j}$$

Where $\mu_j = \frac{1}{n}\sum_{i=1}^{n} \bar{x}_{ij}$ is the mean and $\sigma_j = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\bar{x}_{ij} - \mu_j)^2}$ is the standard deviation for variable j. This transformation ensures each variable has a mean of zero and a unit variance, $Z_j \sim N(0,1)$, for each variable.

Because the selected indices originate from different reporting years, all data were treated as a cross-sectional snapshot of current country performance, represented as $X_i = [Z_{i1}, Z_{i2}, \dots, Z_{ip}]$, without temporal interpolation.

Finally, outliers were examined to prevent disproportionate influence on the PCA results. While z-score standardisation mitigates the effect of extreme values, potential distortions (e.g., unusually high VC investments) were further evaluated. When necessary, robust adjustment through Winsorisation was applied according to $Z_{ij}^{\text{winsor}} = \min(\max(Z_{ij}, L), U)$, where L and U represent the lower and upper percentile thresholds, respectively. This approach maintains data integrity while reducing the leverage of outliers in the multivariate analysis.

4. Results

To explore the underlying structure of the dataset and identify the key dimensions driving cross-country variation, a principal component analysis (PCA) was conducted. This technique reduces the complexity of multivariate data by transforming correlated variables into a smaller set of uncorrelated components, allowing for a clearer understanding of the dominant patterns while retaining most of the original information.

The first principal component (PC1) captures the majority of the variance in the dataset, accounting for 62.68%, indicating that a single underlying factor, a combination of Green Growth, Ocean Health, Venture Capital, CPI, and reversed Innovation Rank, largely explains cross-country differences. PC1 can be interpreted as a general sustainability and innovation strength dimension, where countries scoring high across most variables also have high PC1 values. The second principal component (PC2), orthogonal to PC1, explains an additional 19.52% of variance, capturing patterns not accounted for by PC1, such as countries that are strong in innovation but weaker in ocean health, or vice versa. Together, PC1 and PC2 explain approximately 82% of the total variance, providing excellent coverage and ensuring that a two-dimensional PCA biplot meaningfully represents both country positioning and the contributions of the variables.

Table 2 **:** Variance Explained by Principal Components

Principal Component	Variance Ratio	Percentage
PC1	0.6268	62.68%
PC2	0.1952	19.52%

Source: Author’s analysis

Building on the variance explained by the principal components, it is important to examine the loadings, which indicate how strongly each original variable contributes to a component. Positive loadings show that the variable moves in the same direction as the component, with higher absolute values reflecting greater influence. Loadings can thus be interpreted as the weight of each variable in defining the component.

Table 3: PC1 Interpretation (62.68% variance)

Variable	Loading	Interpretation
Green Growth Index	0.699	Moderately strong contribution to PC1
Ocean Health score	0.373	Moderate positive contribution
Venture Capital	0.950	Very strong contribution
Corruption Perceptions Index	0.950	Very strong contribution
Global Innovation Rank (Reversed)	0.898	Strong contribution

Source : Author's analysis

PC1 is heavily dominated by Venture Capital, CPI, and Innovation Rank, with Green Growth contributing moderately and Ocean Health having a smaller influence. This suggests that PC1 represents a development, governance, and innovation strength dimension, where countries scoring high are wealthy, innovative, and well-governed, while environmental performance plays a secondary role.

Table 4 **:** PC2 Interpretation (19.52% variance)

Variable	Loading	Interpretation
Green Growth Index	0.326	Moderate positive contribution
Ocean Health score	0.880	Very strong contribution
Venture Capital	-0.239	Small negative contribution
Corruption Perceptions Index	-0.239	Small negative contribution
Global Innovation Rank (Reversed)	-0.113	Minimal negative contribution

Source : Author's analysis

PC2, orthogonal to PC1, is strongly influenced by Ocean Health, with minor negative contributions from Venture Capital, CPI, and Innovation. It captures the environmental versus economic/innovation trade-off, highlighting countries with strong ocean and environmental performance irrespective of their economic or innovation standing.

Building on the interpretation of the principal components and their loadings, the next step is to examine how individual countries are positioned in the reduced two-dimensional PCA space. This provides insight into their relative performance along the key dimensions of development, governance, innovation (PC1) and environmental performance (PC2).

Table 5: PCA Transformed Coordinates of Countries

Country	PC1 Coordinate	PC2 Coordinate
Sweden	2.218284	0.103095
Denmark	2.569886	-0.416053
Norway	1.733880	-0.283201
Netherlands	1.605394	-0.916407
Germany	1.805031	0.087509
France	1.313597	0.805619
United Kingdom	2.176735	2.702472
Finland	2.414815	-0.356189
Canada	1.144313	-0.988506
United States	1.123643	0.336861
Japan	1.258930	0.132805
Singapore	1.257502	-2.614737
Australia	1.403711	0.517818
Republic of Korea	0.616834	-0.682437
Switzerland	2.288943	-0.213614
Morocco	-2.233581	-0.534462
South Africa	-1.931349	-0.523108
Kenya	-2.758636	0.736227
Rwanda	-1.578250	0.058423
Brazil	-1.412618	1.032376
Mexico	-1.845437	1.772340
Chile	0.039133	0.207351
India	-1.854768	-1.236958
Indonesia	-1.723162	-0.434587
Vietnam	-1.345019	-0.404382
Turkey	-1.282709	0.793574

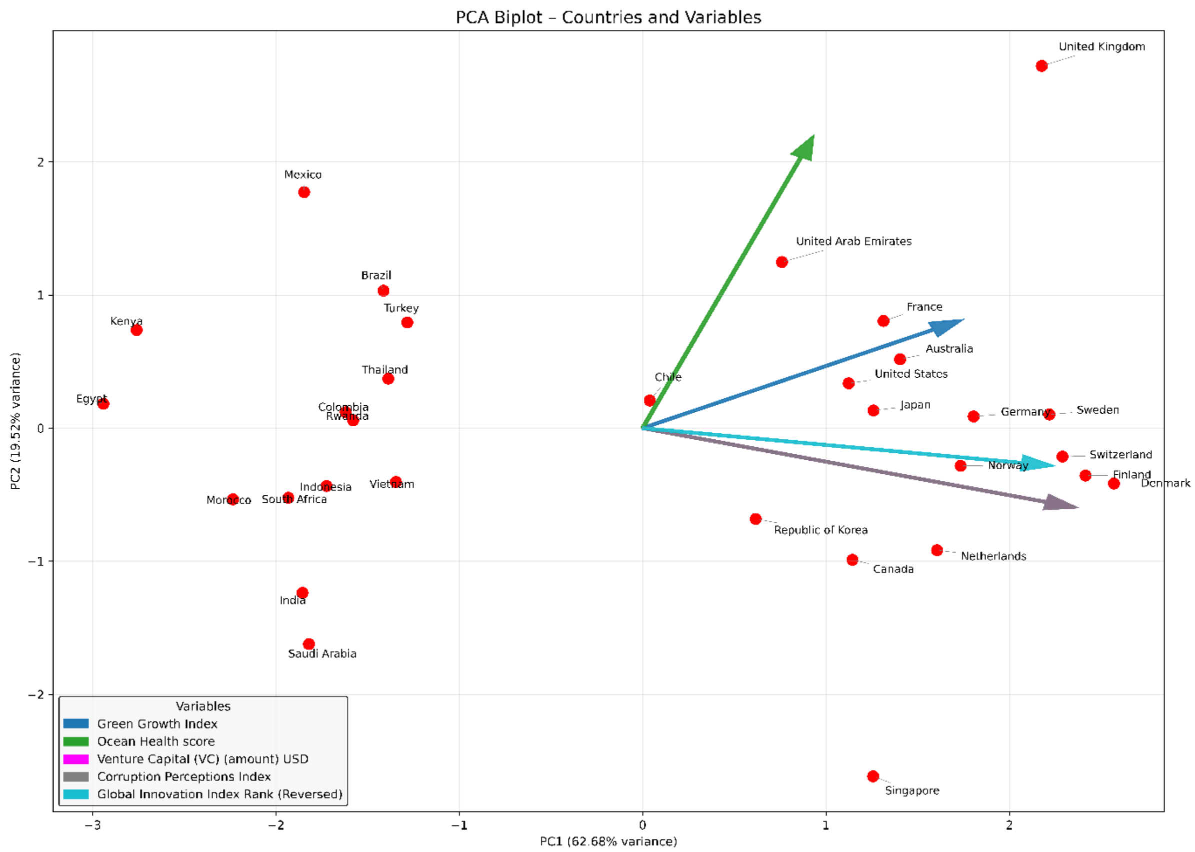
Saudi Arabia	-1.819692	-1.621889
United Arab Emirates	0.760100	1.247722
Egypt	-2.939813	0.183175
Thailand	-1.386573	0.371736
Colombia	-1.619124	0.119425

Source : Author's analysis

In the PCA space, PC1 (x-axis) reflects economic, governance, and innovation strength, while PC2 (y-axis) represents environmental performance, mainly Ocean Health, with positive values indicating stronger performance and negative values indicating weaker performance. Countries with high PC1, such as the United Kingdom (2.72), Denmark (2.57), Sweden (2.22), and Switzerland (2.29), are leaders in development, governance, and innovation, though their environmental performance varies, with Denmark slightly negative on PC2 and France (0.81) and Germany (0.09) showing a balanced combination of development and environmental outcomes. High PC2 countries, including the United Kingdom (2.72, 2.72), Brazil (-1.41, 1.03), Mexico (-1.84, 1.77), and the UAE (0.76, 1.25), excel in environmental performance relative to their economic and innovation scores. Low PC1 countries such as Morocco (-2.23), Kenya (-2.76), Egypt (-2.94), and South Africa (-1.93) face challenges in economic development, governance, and innovation, with varying environmental performance. Kenya (~0.73) performs reasonably well environmentally despite low PC1, whereas Egypt (0.18) is weak on both dimensions. India (-1.85, -1.23) and Saudi Arabia (-1.82, -1.62) score low on both PC1 and PC2, indicating weaknesses in development and environmental outcomes, while mid-range countries like Chile (0.04, 0.21), Thailand (-1.38, 0.37), and Colombia (-1.62, 0.12) show moderate environmental performance but limited development and innovation. Overall, Western European countries dominate PC1, highlighting strong governance, innovation, and venture capital support, while environmental performance (PC2) does not always correlate with development, as seen in Mexico and Brazil. African and Middle Eastern countries generally score low on PC1, although some, like Kenya and Turkey, display moderate environmental strength, and the PCA biplot clearly separates countries into quadrants: top-right for those strong in both development and environmental performance, top-left for environmentally strong but less developed countries, and bottom-left for countries lagging on both dimensions.

Extending the PCA analysis of country positioning and variable loadings, the PCA Biplot for Countries and Variables provides a comprehensive visual representation that illustrates the relationships between countries and the measured indicators. The plot is defined by the two principal components: PC1 (horizontal axis), and PC2 (vertical axis). Countries depicted as red dots that are close to each other share similar profiles, while their position relative to the origin and the variable arrows indicate scores on specific variables. The colored arrows represent variables, with longer arrows indicating better representation and angles between arrows reflecting correlations: small angles suggest positive correlation, angles near 90° indicate minimal correlation, and angles near 180° suggest negative correlation. PC1 clearly separates countries along the main development dimension: highly developed nations, Western European and Anglosphere countries, whereas emerging economies appear on the left with lower scores. Strong positive correlations exist among Green Growth, Ocean Health, and Innovation, while the Corruption Perceptions Index points in the opposite direction, indicating that countries with high scores in development and sustainability tend to have lower perceived corruption. Venture Capital shows a slightly different pattern, pointing toward the lower-right, moderately correlated with the other positive indicators. Notable country positions include outliers such as the United Kingdom and United Arab Emirates, which score very high on PC2 and slightly high on PC1, reflecting exceptional environmental performance, while Singapore stands out in the lower-right due to high Venture Capital and Innovation scores but lower environmental performance. Nordic countries cluster tightly at the top-right, highlighting their combined strengths in development, governance, and sustainability, whereas India and Saudi Arabia occupy the lower-left quadrant, reflecting low scores across both development and environmental dimensions. Mid-left clusters, including Brazil, Turkey, Thailand, Colombia, and South Africa, show moderate to low performance on key indicators. Overall, the PCA Biplot effectively reveals a strong divide primarily along PC1, distinguishing highly developed, innovative, and low-corruption countries from emerging economies, and underscores positive correlations among key development and sustainability indicators.

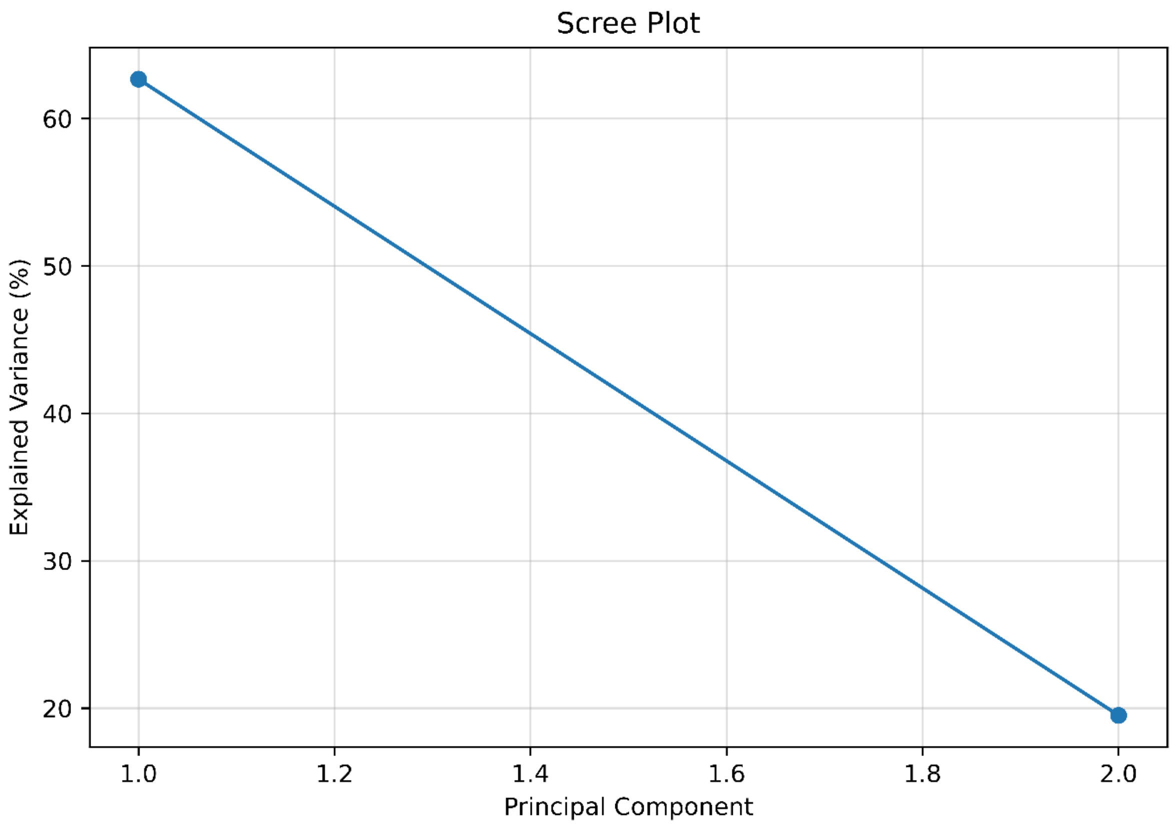
Figure 1: Principal Component Analysis (PCA) Biplot of Countries and Variables



Source: Author's analysis

Following the insights gained from the PCA Biplot, the Scree Plot provides a complementary visual tool to assess the optimal number of principal components to retain for further analysis. This plot displays the Explained Variance (%) for each Principal Component (PC) along the X-axis (component number) and Y-axis (variance explained), showing that PC1 accounts for approximately 63% of the variance and PC2 explains about 20%, which aligns with the PCA Biplot findings. To determine the number of components to keep, two common rules are considered: the "Elbow" Rule suggests retaining components up to the point where the explained variance curve begins to flatten, and although only two components are shown here, the steep drop from PC1 to PC2 supports retaining both, as together they explain roughly 83% of the total variance. The "Eigenvalue > 1" Rule (Kaiser Criterion) also supports this choice, as both PC1 and PC2 explain substantially more variance than a single standardized variable would, indicating their significance. Overall, the Scree Plot confirms that PC1 is the dominant component while PC2 captures a substantial portion of the remaining variance, justifying the selection of the first two components for the analysis and visualization, seamlessly complementing the PCA Biplot interpretation.

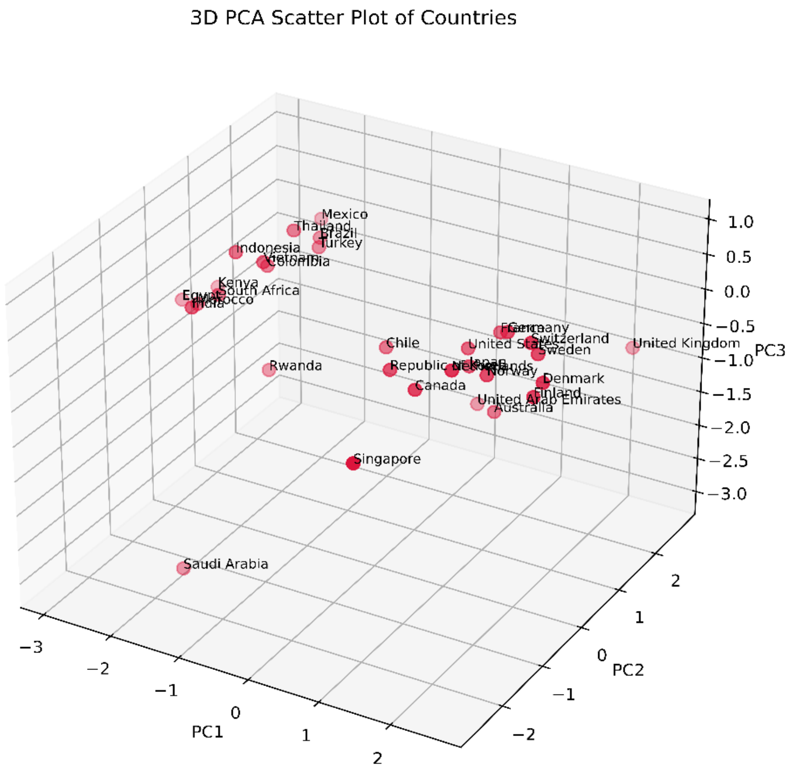
Figure 2: Scree Plot of Explained Variance by Principal Component.



Source: Author’s analysis

Extending the analysis from the 2D PCA visualisations, the 3D PCA Scatter Plot of countries incorporates the first three principal components (PC1, PC2, and PC3) to capture additional variance and provide a more nuanced view of the data. PC1 continues to distinguish Developed/High-Performer nations (positive values) from Emerging Economies (negative values), while PC2 maintains its role in differentiating environmental and economic/innovation performance. The addition of PC3, although its exact explained variance is not specified, captures residual variation, allowing countries that overlapped in the 2D view to be more clearly separated. The 3D plot reinforces the key country groupings observed previously: High-performing developed nations like Switzerland, Sweden, Germany, Finland, and Denmark cluster tightly on the positive side of PC1, with the United Kingdom appearing as an outlier high on PC2 and positive on PC3, reflecting its distinctive profile in Venture Capital and Ocean Health. Emerging economies, including Mexico, Turkey, Thailand, Brazil, Colombia, Indonesia, and South Africa, form a lower-scoring cluster on negative PC1 values, with Kenya and Egypt representing the lowest scores on the primary development axis. Notable outliers such as Saudi Arabia, positioned far negative on both PC1 and PC2, and Singapore, negative on PC2 but near the origin on PC1, highlight unique country profiles that diverge from the main clusters. Overall, the 3D visualisation confirms the two dominant clusters identified in the 2D analyses, while PC3 introduces additional differentiation, emphasizing the heterogeneity in development, governance, innovation, and environmental performance across countries.

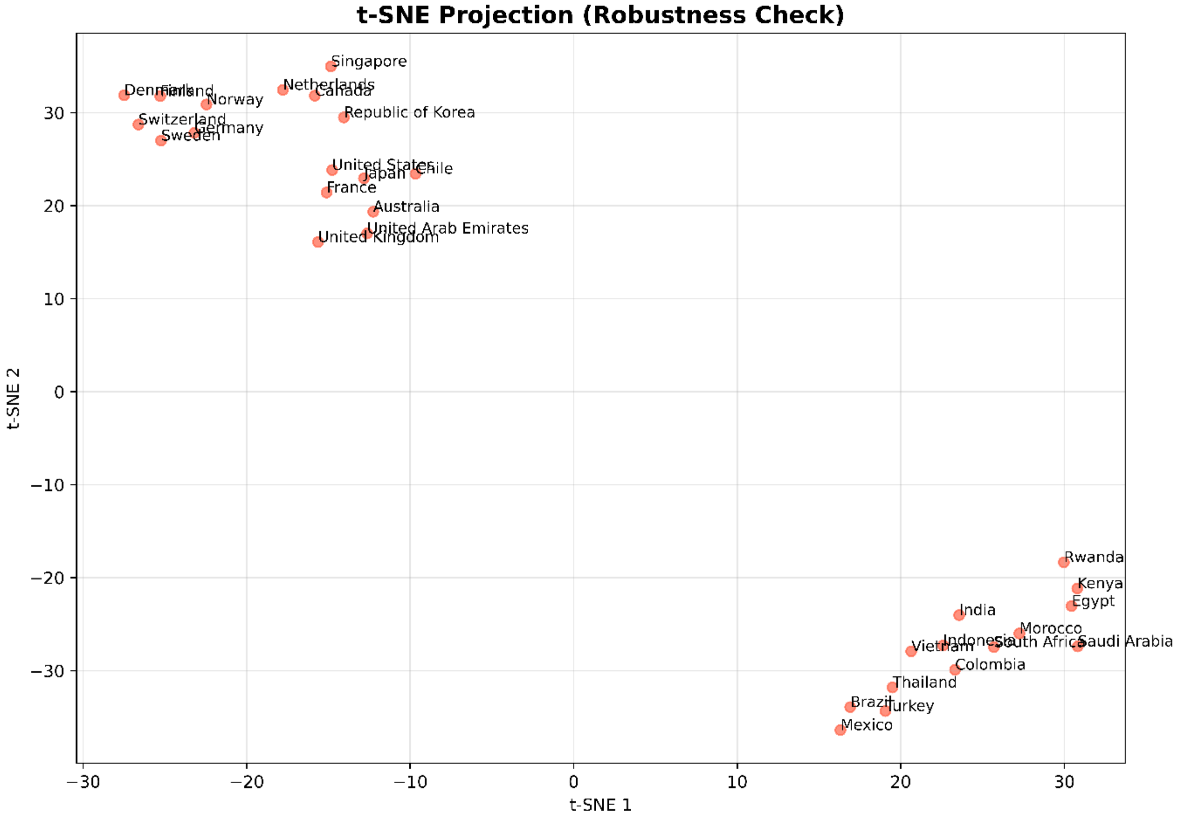
Figure 3: Three-Dimensional Scatter Plot of Country Coordinates on the First Three Principal Components (PC1, PC2, and PC3).



Source: Author's analysis

Drawing on the insights from the 3D PCA Scatter Plot, the scatter plot of K-Means Clustering in the PCA space (PC1 vs. PC2) clarifies and formalises the groupings observed in the PCA analyses by separating the countries into three distinct clusters (K=3), each marked by a different color. Cluster 1 (Teal/Dark Cyan), mainly on the negative side of PC1, includes Emerging Economies and lower-performing countries such as Mexico, Brazil, Turkey, Thailand, Colombia, Rwanda, Indonesia, Vietnam, South Africa, Morocco, India, Saudi Arabia, Kenya, and Egypt, reflecting low scores on key positive indicators like Green Growth, Global Innovation Rank (Reversed), and Ocean Health, alongside higher corruption levels. Cluster 2 (Yellow), primarily on the positive side of PC1, consists of Developed or high-performing countries such as the United Kingdom, United Arab Emirates, France, United States, Australia, Japan, Germany, Sweden, Norway, Switzerland, Finland, Denmark, Canada, Netherlands, and Chile, which score high on innovation, sustainable growth, and ocean health while exhibiting low corruption. Cluster 3 (Purple) identifies distinct outliers, notably Singapore, positioned low on PC2 but high on PC1, indicating a unique combination of strong innovation and green growth with comparatively lower environmental performance. The K-Means clustering thus confirms the main divisions among countries and highlights exceptional cases within the dataset.

Figure 4: t-distributed Stochastic Neighbor Embedding (t-SNE) Projection of Countries (Robustness Check).



Source: Author's analysis

Based on the K-Means clustering results, the data highlights the composition and profiles of the three identified clusters in the PCA space. Cluster 0 consists solely of Singapore, an outlier with a distinctive combination of variable scores, high on PC1-related indicators like Innovation and Green Growth but low on PC2-related factors such as Ocean Health. Cluster 1, positioned mostly on the negative side of PC1, includes Brazil, Colombia, Egypt, India, Indonesia, Kenya, Mexico, Morocco, Rwanda, Saudi Arabia, South Africa, Thailand, Turkey, and Vietnam, representing Emerging Economies with generally lower performance on sustainable growth, innovation, and environmental health, along with higher perceived corruption. Cluster 2, located mainly on the positive side of PC1, includes Australia, Canada, Chile, Denmark, Finland, France, Germany, Japan, Netherlands, Norway, Republic of Korea, Sweden, Switzerland, United Arab Emirates, United Kingdom, and the United States, reflecting Developed Nations with strong performance across Green Growth, Innovation, and Ocean Health and low corruption. Collectively, the clustering categorises countries into three distinct groups: the largest group of Emerging Economies, the Developed Nations cluster, and the unique outlier Singapore, whose particular profile sets it apart from the other clusters.

Table 6: Countries by Cluster Assignment

Cluster	**Countries**
0	**Singapore**
1	**Morocco, South Africa, Kenya, Rwanda, Brazil, Mexico, India, Indonesia, Vietnam, Turkey, Saudi Arabia, Egypt, Thailand, Colombia**
2	**Sweden, Denmark, Norway, Netherlands, Germany, France, United Kingdom, Finland, Canada, United States, Japan, Australia, Republic of Korea, Switzerland, Chile, United Arab Emirates**

Source: Author's analysis

Examining the cumulative variance explained by the principal components shows that PC1 alone accounts for 62.68% of the variance, primarily reflecting economic, governance, and innovation strength. Including PC2 increases the explained variance to 82.20%, adding the environmental dimension, mainly Ocean Health, and providing a very good two-dimensional representation of most of the dataset's variability. Adding PC3 raises the cumulative variance captured to 94.61%, meaning nearly all information in the dataset is summarized and allowing finer distinctions between countries that may not be apparent in two dimensions. This indicates that using three principal components is sufficient for most analyses, such as clustering, visualization, or robustness checks, while the first two components already provide a meaningful representation (~82%), which explains the relevance of the 2D biplot and K-Means clustering on PC1 and PC2. In summary, PC1 dominates the overall structure, PC2 introduces environmental contrast, and PC3 contributes minor additional variance (<13%) that can highlight subtle differences among countries.

Table 7 : Cumulative Explained Variance (3 Components)

Principal Component (PC)	**Cumulative Variance Explained (%)**
PC1	62.67899301
PC2	82.19713515
PC3	94.61183897

Source : Author's analysis

Applying Varimax rotation to the principal components clarifies the interpretation by maximising the variance of squared loadings, pushing variables to load strongly on one component while remaining orthogonal (uncorrelated). After rotation, PC1 primarily reflects economic, governance, and innovation strength, with strong contributions from Venture Capital (0.579) and the Corruption Perceptions Index (0.579), moderate input from Global Innovation Rank (Reversed, 0.501), and minimal influence from environmental factors such as Green Growth (0.220) and Ocean Health (−0.172). In contrast, PC2 becomes a largely independent environmental dimension, dominated by Ocean Health (0.884) and complemented by Green Growth (0.456), while all other variables contribute minimally (0–0.103). This rotation effectively separates the development/innovation/governance dimension

(Rotated PC1) from the environmental dimension (Rotated PC2), making the interpretation of biplots, clusters, and country positions more straightforward and highlighting the distinct roles of socio-economic versus environmental factors.

Table 8: Rotated PCA Loadings (Varimax)

Original Variable	Rotated PC1 Loading	Rotated PC2 Loading
Green Growth Index	0.220	0.456
Ocean Health score	-0.172	0.884
Venture Capital (VC) (amount) USD	0.579	0.000
Corruption Perceptions Index	0.579	0.000
Global Innovation Index Rank (Reversed)	0.501	0.103

Source : Author's analysis

5. Discussion

1. Synthesis of principal findings

The analysis uncovers a stable, interpretable cross-country structure at the interface of development, governance, innovation, and environmental performance. PC1 explains ~62.7% of total variance and loads very strongly on venture capital and cleaner governance (higher CPI scores), with a strong contribution from innovation capacity (reversed GII rank), a moderate contribution from green growth, and a smaller one from ocean health. PC2, orthogonal to PC1 and explaining ~19.5% of variance, is dominated by ocean health with a moderate contribution from green growth and small negative associations with venture capital and CPI. Together, PC1 and PC2 account for ~82.2% of variance; adding PC3 raises cumulative coverage to ~94.6%. Varimax rotation clarifies a development–innovation–governance (Rotated PC1) axis distinct from an environmental/ocean-health (Rotated PC2) axis. K-means clustering in the PCA space identifies three regimes: a singleton outlier (Singapore), a large set of emerging/lower-performing economies (negative PC1, mixed PC2), and a developed/high-performer group (positive PC1, mixed but often favorable PC2).

2. Interpreting components in light of prior evidence

PC1: A development–innovation–governance finance gradient

The prominence of PC1, with heavy positive associations for risk capital, cleaner governance, and innovation capability, is consistent with ecosystem and national-innovation-systems scholarship emphasizing co-evolution among institutions, finance, and capabilities (Stam, 2015; Jacobsson & Bergek, 2011). Strong, credible governance reduces uncertainty and supports long-horizon clean-technology investment (Kaufmann, Kraay, & Mastruzzi, 2011; Aghion, Dechezleprêtre, Hémous, Martin, & Van Reenen, 2016; Ambec, Cohen, Elgie, & Lanoie, 2013). The centrality of venture capital accords with evidence that risk capital underpins scale-up of capital-intensive clean technologies yet is highly sensitive to policy signals and institutional quality (Gaddy, Sivaram, & O'Sullivan, 2018; Nanda, Younge, & Fleming, 2015), and with recent international evidence linking corporate-governance quality to green innovation (Makpotche, Bouslah, & M'Zali, 2024).

PC2: An environmental/blue-economy dimension

PC2's very strong loading on ocean health and moderate loading on green growth indicate that environmental performance is partially independent of the development–finance–innovation complex. This interpretation aligns with blue-economy research showing that healthier marine ecosystems measured by the Ocean Health Index underpin provisioning, regulating, and cultural services (Halpern et al., 2012) and with policy frameworks (MSP, blue bonds) designed to translate ocean natural capital into resilient socio-economic outcomes (OECD, 2016; Ehler & Douvere, 2009; World Bank, 2018).

3. Country regimes and comparative insights

Developed/high-performer cluster. Countries on the positive side of PC1 (e.g., many Western European and Anglosphere economies) combine innovation capacity, deeper risk-capital markets, and cleaner governance conditions known to crowd-in private clean investment and enable directed technical change (Aghion et al., 2016; Mazzucato, 2018; Costantini, Crespi, & Palma, 2017). Variation in PC2 within this group suggests that ocean outcomes are not automatic by-products of innovation prowess; rather, they require marine-specific governance and spatial planning (World Bank, 2018).

Emerging/lower-performer cluster. The large negative-PC1 cluster is characterized by shallower innovation-finance systems and governance gaps. Nonetheless, PC2 heterogeneity reveals instances of moderate ocean performance relative to development capacity consistent with complex adaptive systems (CAS) perspectives in which policy-led environmental gains are feasible even when innovation–finance capabilities are still consolidating (Geels, 2002; Markard, Raven, & Truffer, 2012; UNDP, 2023). Persistent corruption continues to erode green-innovation payoffs and implementation quality (Mauro, 1995; Wen, 2023; Kaufmann et al., 2011).

The Singapore singleton. Singapore's combination of high PC1 with comparatively lower PC2 in this sample illustrates that frontier innovation–finance-governance ecosystems may underperform on specific environmental sub-domains absent targeted instruments (e.g., MSP, ecosystem-service safeguards) (Ehler & Douvere, 2009; Laurans, Rankovic, Billé, Pirard, & Mermet, 2013). This outlier underscores the utility of a two-axis reading: excellence on the development–innovation–governance axis need not entail uniformly high ocean performance.

4. Convergences and divergences with prior empirical work

Convergences. The dominance of the innovation-governance-finance axis (PC1) accords with multi-country evidence that credible policy and institutional quality are decisive for green-technology investment and diffusion (Ambec et al., 2013; Aghion et al., 2016; Gaddy et al., 2018). The partial independence of environmental performance (PC2) aligns with blue-economy syntheses emphasizing MSP and blue bonds to convert ocean natural capital into resilient socio-economic outcomes (OECD, 2016; World Bank, 2018). The clustering of advanced economies on PC1 is consistent with ecosystem scholarship on complementarities among innovation capacity, finance, and governance (Stam, 2015; Jacobsson & Bergek, 2011).

Divergences. Some high-PC1 countries exhibit middling PC2 scores, diverging from assumptions of linear co-movement between innovation and environmental outcomes and pointing to marine-policy gaps (Halpern et al., 2012; Wabnitz et al., 2021). Conversely, several emerging economies display moderate PC2 despite weak PC1, consistent with CAS views of multiple, non-linear transition routes (Geels, 2002; Markard et al., 2012).

5. Explaining the differences

Policy credibility and finance complementarities. Carbon pricing, stable standards, and mission-oriented programs mobilize private VC and steer inventive effort toward cleaner trajectories, amplifying PC1 advantages (Aghion et al., 2016; Mazzucato, 2018; Costantini et al., 2017).

Marine governance specificity. Ocean outcomes respond to MSP quality, enforcement, and blue-finance pipelines, not merely to general innovation capacity explaining PC2 dispersion among high-PC1 countries (Ehler & Douvere, 2009; World Bank, 2018).

Institutional frictions. Corruption and weak rule-of-law depress the returns to green policy and innovation subsidies, shifting countries toward the negative side of PC1 and blunting environmental initiatives (Mauro, 1995; Wen, 2023; Kaufmann et al., 2011).

6. Robustness and credibility

The design direction-aligned standardization, PCA with clear dominance of the first two components, varimax rotation separating development–innovation–governance from environmental performance, and clustering in PCA space complemented by t-SNE accords with best practice in multivariate synthesis (Abdi & Williams, 2010; Jolliffe & Cadima, 2016; Hubert, Rousseeuw, & Vanden Branden, 2005; van der Maaten & Hinton, 2008; Rousseeuw, 1987; Tibshirani, Walther, & Hastie, 2001). The high cumulative variance (~94.6% with three components) supports interpretability; rotated loadings improve construct clarity; and the three-regime solution is theoretically congruent.

7. Policy and managerial implications

For advanced innovators. Complement innovation-finance strengths with marine-specific instruments (upscaled MSP, blue-bond pipelines, and coastal ecosystem restoration) to convert PC1 advantages into consistently high ocean outcomes (World Bank, 2018)

For emerging economies. Sequence reforms to build institutional credibility (anti-corruption, regulatory streamlining) that raise PC1, while protecting or improving PC2 via targeted blue-economy investments during capability accumulation (UNDP, 2023).

For investors. Integrate governance risk and blue-natural-capital metrics into due diligence to locate contexts where policy credibility and ecosystem assets jointly de-risk green business models (Gaddy et al., 2018).

8. Limitations and future research

The synthesis is cross-sectional a snapshot compiled from proximate yet non-identical reporting years so temporal dynamics and policy lags are not modeled. Rank-based measures (GII) were direction-reversed and standardized, though factor solutions can remain sensitive to indicator choice. Future work could introduce panel structure to identify policy shocks and diffusion dynamics, probe cluster stability with alternative validity indices and bootstrapping, and incorporate richer blue-economy measures (e.g., MPA effectiveness, coastal risk-reduction services) to refine PC2 interpretability (Jolliffe & Cadima, 2016 ; Wabnitz et al., 2021).

6. Managerial and Policy Implications

The results indicate that institutional credibility, venture-capital depth, and innovation capacity jointly underpin sustainable entrepreneurial ecosystems. For public decision-makers, this implies that transparent, predictable, and corruption-resistant governance frameworks are a pre-condition for mobilizing private green investment and sustaining long-horizon innovation bets (Kaufmann, Kraay, & Mastruzzi, 2011 ; Aghion, Dechezleprêtre, Hémous, Martin, & Van Reenen, 2016). Aligning industrial and innovation policy with climate goals through mission-oriented programs linking public R&D, fiscal incentives, and climate-finance instruments helps convert policy credibility into durable technological and competitive advantages (Mazzucato, 2018 ; Costantini, Crespi, & Palma, 2017).

For investors and firms, the tight coupling between cleaner governance and active VC markets suggests that institutional due diligence should weigh as heavily as financial metrics when allocating green or blue-economy capital. Stable rules reduce transaction costs and facilitate collaboration within entrepreneurial ecosystems (Stam, 2015), while robust corporate governance is associated with stronger green-innovation outcomes (Makpotche, Bouslah, & M'Zali, 2024). Because environmental performance (PC2) is partly independent from the development/finance/innovation axis, leadership on marine and broader environmental indicators requires domain-specific strategies e.g., marine spatial planning (MSP), blue bonds, and coastal risk management rather than generic innovation spending (Ehler & Douvere, 2009; World Bank, 2018; OECD, 2016).

International development agencies can tailor support to the observed country regimes : prioritizing institutional-capacity building where governance credibility is weak, and scaling ecosystem-integration tools (e.g., MSP and blue-finance pipelines) where marine opportunities are underexploited. Such differentiation is consistent with OECD (2016) diagnostics on the ocean economy and with World Bank guidance on blue-finance structuring (World Bank, 2018).

7. Recommendations for Developing Economies

1) Governance and institutional credibility.

Strengthen anti-corruption enforcement, judicial independence, and administrative transparency to raise investor confidence and magnify the returns to innovation and environmental programs (Mauro, 1995 ; Wen, 2023 ; Kaufmann et al., 2011). Practical steps include open-data portals and e-governance platforms to reduce information asymmetries and administrative delays.

2) Green-finance ecosystem development.

Use blended-finance facilities, public guarantees, and sovereign green/blue bonds to de-risk early-stage clean technologies and crowd-in private capital. Evidence shows that structured support and guarantees can unlock investment, while well-designed blue bonds (e.g., Seychelles) channel funds toward marine sustainability (Gaddy, Sivaram, & O'Sullivan, 2018; UNDP, 2023; World Bank, 2018). Complementary research documents the catalytic role of VC and public co-investment in cleantech scale-ups (van den Heuvel & Popp, 2022) and the positive impact of VC on green innovation (Yang, 2022).

3) Innovation capacity and human capital.

Invest in STEM education, applied research, and university–industry linkages to expand absorptive capacity and adapt global sustainability innovations locally ; targeted incubators/accelerators for circular and blue-economy ventures can speed firm formation (Jacobsson & Bergek, 2011 ; Nanda, Younge, & Fleming, 2015).

4) Blue-economy integration.

Because the environmental dimension is distinct in the results, coastal economies should mainstream MSP and ocean-health metrics into development planning, leveraging blue-finance mechanisms to support fisheries reform, MPA effectiveness, and coastal resilience (Ehler & Douvere, 2009 ; OECD, 2016 ; World Bank, 2018 ; UNDP, 2023).

5) Sequencing and feedbacks.

A pragmatic sequence governance credibility → financial deepening → capability building → environmental mainstreaming reflects the complex-adaptive nature of sustainability transitions, where reinforcing feedbacks between institutions, finance, and ecological assets shape long-run competitiveness (Markard, Raven, & Truffer, 2012 ; Geels, 2002).

8. Conclusion

This study demonstrates that cross-country sustainability performance can be parsimoniously described along two dominant axes : a Development-Governance-Innovation dimension (PC1) and an Environmental Sustainability dimension (PC2). The high variance explained by the first two components (≈82%) indicates that institutional credibility and innovation capacity are as consequential as ecological indicators in shaping national profiles. Cluster analysis further reveals a divide between advanced ecosystems where credible governance, deep risk-capital markets, and robust innovation capabilities align and emerging ecosystems confronting institutional and financial frictions. The Singapore outlier illustrates that frontier innovation and finance do not automatically translate into strong ocean outcomes, reinforcing the need for domain-specific marine policy.

Theoretically, the results accord with complex adaptive systems accounts in which governance, finance, innovation, and environmental outcomes co-evolve (Geels, 2002 ; Stirling, 2011). Practically, they emphasize policy coherence : anti-corruption measures and predictable rules (raising PC1) should be paired with mission-oriented tools and green/blue finance to crowd-in private investment and deliver measurable environmental gains. Future work should extend the analysis to panel settings to capture policy shocks and diffusion dynamics, incorporate additional green-finance and marine-governance indicators, and test the stability of clusters under alternative specifications. By combining quantitative evidence with system-level theory, the study advances a data-informed framework for managing the intertwined green and blue transitions.

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