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***Economic Theory***

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# INTERPLAY OF HUMAN CAPITAL AND SUSTAINABLE DEVELOPMENT: A NETWORK APPROACH

## Abstract

This paper reveals complex interdependencies between human capital and sustainable development using Bayesian Network Analysis (BNA). Human capital is proxied through the Social Progress Index (SPI) and its components – Basic Human Needs, Foundations of Wellbeing, and Opportunity – alongside the Human Capital Index (HCI) and Sustainable Development Goals metrics. The analysis identifies vital hubs, such as health (SDG 3), sustainable cities (SDG 11), and economic growth (SDG 8), which act as pivotal drivers of systemic progress. Additionally, critical trade-offs, such as the negative association between resource consumption (SDG 12) and human well-being, are uncovered, highlighting the complexity of balancing competing priorities. The findings emphasize the importance of focusing on health, education, and inclusivity to optimize synergies and



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mitigate trade-offs between human capital and sustainability outcomes. By employing Bayesian networks, this study provides a data-driven framework for understanding causal pathways and offers actionable insights for policymakers. These results advance the discourse on integrating human capital investments with sustainable development strategies, addressing gaps in prior linear and correlation-based analyses.

## Key Words:

Bayesian Network Analysis, human capital, Social Progress Index (SPI), sustainable development.

**JEL:** O15, Q01, C11.

3 tables, 6 figures, 38 references.

## Problem Statement

The interplay between human capital and sustainable development has garnered significant attention in academic and policy circles due to its pivotal role in addressing global challenges, including inequality, environmental degradation, and economic instability. Human development and sustainable development constitute a complex, dynamic system, in which each concept influences and reinforces the other. Human capital development, encompassing education, health, and skills, is a cornerstone of financial resilience and societal well-being. Sustainable development, by contrast, focuses on balancing economic growth, environmental stewardship, and social equity. These concepts form an interdependent framework for fostering long-term prosperity and sustainability.

The nuanced relationships among the components of these concepts are critical to understanding how they collectively foster long-term economic growth and societal well-being within a complex system. These concepts interact as a

holistic framework in which causal relationships among education, health, environmental sustainability, and societal equity shape development trajectories.

The causal pathways linking human and sustainable development underscore the centrality of human capital in achieving transformative outcomes. According to the United Nations Development Programme (1990), human development is not solely about economic growth, but about creating an environment in which individuals can reach their full potential and lead fulfilling lives. Improvements in education and health, which are critical dimensions of human capital, empower individuals and serve as precursors to broader societal benefits. For instance, healthier and better-educated populations are more likely to innovate, adapt, and contribute to sustainable solutions, creating a positive feedback loop between individual development and societal progress (Sen, 1999).

Revealing the complex, nuanced causal relationships among these components is essential to understanding how investments in human development translate into sustainable development outcomes. Empirical evidence shows that education and skill development enhance individuals' capabilities to engage with knowledge-intensive sectors and innovation-driven industries (Kuryliak et al., 2025). These sectors, in turn, generate economic resilience and environmental sustainability by fostering greener technologies and more efficient resource management practices (Barro & Lee, 2013; Lucas, 1988; Maksymova et al., 2023).

Despite extensive research on this topic, several gaps remain. Much of the existing literature relies on linear or correlation-based analyses, which fail to capture the complex causal relationships and feedback loops inherent in the human capital-sustainability nexus. Furthermore, studies often overlook the multidimensionality of human capital, typically addressing education and health in isolation rather than examining their integrated impact on sustainable development outcomes. Another underexplored area is the role of governance and socioeconomic context in mediating these relationships, which is critical for tailoring effective interventions.

This paper addresses gaps by employing Bayesian Network Analysis (BNA), a probabilistic graphical modeling technique, to examine the nuanced causal relationships among human capital, its components, and the Sustainable Development Goals (SDGs). By integrating comprehensive indices, including the Social Progress Index (SPI) and its components (Basic Human Needs, Foundations of Wellbeing, and Opportunity), the Human Capital Index (HCI), and SDG metrics, the study provides a detailed understanding of how investments in human capital translate into sustainable development outcomes.

**The primary objective of this paper** is to reveal the causal pathways and interdependencies between human capital and sustainable development. Specifically, the study addresses the following research questions:

1) What are the key causal relationships between human capital components and the Sustainable Development Goals (SDGs)?

2) How do trade-offs and synergies among these relationships inform policy strategies for achieving sustainable development?

The paper's structure is as follows: Literature Review examines the existing body of research on the human capital – sustainability nexus, identifying gaps and positioning this study within the broader academic discourse. Methodology details the data sources, variables, and the Bayesian network modeling approach used to uncover causal relationships. The Results and Discussion sections present the findings, highlighting key hubs, interdependencies, and trade-offs, and discuss their implications for policy and practice. The Conclusion synthesizes the insights gained and emphasizes the contributions of this study.

This paper addresses research questions and employs an innovative methodological framework to contribute to ongoing discussions on human capital and sustainable development. It offers actionable insights for policymakers and stakeholders navigating global sustainability challenges.

## Literature Review

Human capital, encompassing education, health, and skills, plays a pivotal role in sustainable development by fostering economic growth, reducing environmental degradation, and promoting social equity. Scholars have extensively examined this relationship using theoretical models, empirical analyses, and multidimensional indices to assess how investments in human capital contribute to sustainability.

The relationship between human capital and sustainable development underscores the need to invest in education and health to achieve comprehensive socio-economic progress. For instance, Alakbarov et al. (2020) emphasize that effective human capital management is critical for resource-rich countries to mitigate environmental impacts and promote regional sustainable development. Nathaniel (2021) further illustrates how skilled and educated human capital facilitates the sustainable use of natural resources, fostering economic prosperity. These findings are echoed by Olowookere et al. (2022), who assert that investments in education and healthcare improve human resources, reduce poverty, and enhance sustainability outcomes.

Adding a new dimension, Mishchuk et al. (2023) highlight the role of social capital as a complement to human capital, arguing that robust social structures, including trust and networks, can significantly enhance the competitiveness of national economies. This perspective underscores the synergistic relationship be-

tween human and social capital in achieving sustainable development goals, particularly by improving governance and reducing societal transaction costs. Liashenko & Dluhopolskyi (2024, 2025) expand this discussion by linking human capital to societal progress through social welfare preferences and Society 5.0 principles. Their research underscores the importance of aligning human-centric policies with advanced technologies to foster sustainable development outcomes.

The interaction between human capital and environmental sustainability remains a focal point in the literature. Gnangoin et al. (2023) highlight that investments in human capital moderate the relationship between urbanization and CO2 emissions, fostering sustainable urban development. Adikari et al. (2023) discuss human capital's critical role in reducing environmental degradation, primarily through carbon emissions management. Similarly, Şentürk et al. (2023) identify the interdependence among health expenditures, human capital, and sustainable development, emphasizing health as a critical factor in building a productive workforce that drives sustainable economic growth. Governance also plays a pivotal role in enabling these outcomes. Liashenko et al. (2024) emphasize that governance quality, including regulatory frameworks and accountability mechanisms, enhances human capital's contributions to environmental quality and social progress.

Picazo-Tadeo et al. (2024) propose a GDP per capita indicator for EU regions, adjusted for social progress, by integrating economic performance with components of the Social Progress Index. It shows that higher GDP levels do not automatically translate into better social outcomes and underscores the importance of integrated well-being measures for EU regional policy.

Another body of literature emphasizes that the broader socio-economic and institutional environment significantly shapes the quality and impact of human capital. Sanduhei et al. (2025), and Demchenko and Makov (2026) highlight the strategic management of human capital to enhance national competitiveness and drive sustainable development. Khelghat-Doost and Sibly (2020) and Abo-Khalil (2024) propose a framework for integrating sustainability principles into higher education, emphasizing the role of educational institutions in fostering a sustainability-oriented workforce. Lyeonov et al. (2025) examine how quality in higher education, including teaching, research, and institutional performance, drives the development of the knowledge economy. They show that universities contribute to economic competitiveness not only through scale but also through the quality of human capital and knowledge creation. Liashenko et al. (2024) further explore how effective governance mechanisms, such as regulatory quality and anti-corruption measures, enhance human capital's role in social development. Similar views are expressed in the works of Samadov (2024), Losieva (2023), and Lopatynskyi et al. (2020).

Despite extensive research on human capital and sustainable development, several gaps persist. Many studies focus on specific dimensions, such as economic growth or environmental quality, without integrating them into compre-

hensive frameworks. Recent works by Şentürk et al. (2023) and Liashenko et al. (2024) address this gap by employing multidimensional indices, such as the Social Progress Index (SPI), to measure sustainability across diverse domains. Most research establishes correlations without exploring causal loops or causal relationships among partial proxies of human capital (Şentürk et al., 2023). Advanced methodologies, such as discriminant and factor analyses, as demonstrated by Liashenko et al. (2024), provide the most valuable insights into the interdependencies between governance quality, human capital, and sustainability outcomes. Qazi (2025) investigates how different components of the Social Progress Index (SPI) interact and jointly influence a country's overall sustainability performance. The core idea is that social progress is a system, not a set of isolated indicators, and that improvements (or failures) in one area can propagate through others, ultimately shaping national sustainability outcomes. This approach helps policymakers identify leverage points at which targeted social interventions can yield the greatest sustainability gains under uncertainty.

Human capital remains a cornerstone of sustainable development, influencing economic growth, environmental stewardship, and social well-being. However, gaps persist in integrating comprehensive frameworks, analyzing causal pathways, and exploring regional and technological dynamics. Addressing these gaps, as demonstrated by Mishchuk et al. (2023), Kim & Go (2020), and Liashenko & Dluhopolskyi (2024), is necessary to align human development with global sustainability goals.

Moreover, the causal interplay extends to the institutional and policy dimensions that govern these processes. Effective governance mechanisms amplify the impact of human development initiatives on sustainable outcomes.

Uncovering the complex web of causal relationships among human and sustainable development components offers a comprehensive understanding of their interdependencies. Education, health, environmental stewardship, and governance do not operate in isolation; instead, they interact dynamically, shaping development pathways and reinforcing the reciprocal relationship between human and sustainable development. This interconnected framework underscores the need for integrative strategies that address all aspects of these concepts, creating a virtuous cycle of progress for individuals, societies, and the planet.

## Methodology

This study aims to examine the nuanced relationships between human capital and sustainable development using advanced quantitative methods and established indices. Specifically, we use components of the Social Progress Index (SPI) as proxies for human capital, namely the Human Capital Index (HCI) and Sustainable Development Goals (SDG) scores.

Bayesian Network Analysis (BNA) is used to reveal complex pathways and interdependencies among these dimensions. The methodology is designed to address gaps in the existing literature by offering a data-driven, nuanced perspective on the interconnections between human capital and sustainable development.

To construct the BNA networks, we used country-level data aggregated over 2022–2024, with global geographic coverage (170 countries). Specifically, for each country, we computed period averages of SPI (and its components) and SDG scores (United Nations Development Programme, 2025) over 2022–2024 to reduce year-specific noise and capture more stable medium-term patterns; HCI is used only in the preliminary flexiplot visualizations (2022 cross-section) and is not included as a node in the BNA networks reported below.

The resulting dataset, therefore, represents a smoothed, cross-sectional view of the system over 2022–2024 rather than short-term fluctuations. Bayesian Network Analysis was implemented in the JASP package. We estimated the network structure using JASP's Bayesian network learning procedure and reported the edge weights and directions as provided by the software. To avoid overstating causality, we interpret directed links as probabilistic dependency pathways consistent with causal hypotheses under standard assumptions, rather than as definitive causal effects. We also rely on the edge evidence probabilities reported by JASP to assess the robustness of the identified links; throughout the discussion, we emphasize stable edges with strong evidence.

Following prior literature (Barro & Lee, 2013; Lucas, 1988), human capital is represented using the Social Progress Index (SPI) components: Basic Human Needs, Foundations of Wellbeing, and Opportunity. The SPI is widely recognized for its multidimensional approach, encompassing critical elements of human well-being beyond traditional economic metrics (Porter et al., 2017). Its use aligns with the study's objective of capturing nuanced dimensions of human capital.

The World Bank developed the Human Capital Index (HCI), which quantifies the productivity potential of future generations using health and education indicators (Kraay, 2019). The HCI ranges from 0 to 1, with higher values indicating greater human capital potential. Sustainable development is proxied by SDG scores, which measure country-level progress towards the SDGs and provide a

comprehensive view of the economic, social, and environmental dimensions. These scores capture the multifaceted nature of sustainability (Sachs et al., 2018).

To uncover nuanced interdependencies between human capital and dimensions of sustainable development, Bayesian Network Analysis (BNA) is employed. Bayesian networks are probabilistic graphical models that represent complex systems using nodes (variables) and edges (causal relationships). They are particularly suited for this study due to their ability to: identify relationships – unlike linear correlation-based methods, BNA enables the detection of directional and probabilistic relationships among variables (Pearl, 2009); handle multidimensional and interdependent data – the method's capacity to analyze high-dimensional data aligns with the complexity of human capital and sustainability metrics; Bayesian inference allows for robust estimations even in the presence of missing or noisy data, ensuring reliable results (Chen & Pollino, 2012).

The adoption of BNA aligns with recent studies exploring causal structures in socio-economic and environmental systems (see, for example, Jebari et al., 2022; Bielza & Larrañaga, 2014).

The integration of SPI components, HCI, and SDG scores addresses a critical gap in the literature by providing a comprehensive view of human capital and sustainability. While prior studies have employed econometric models to analyze these relationships (Barro & Lee, 2013; Lucas, 1988), they often need to account for the multidimensionality and interdependencies inherent in these systems. The adoption of Bayesian Network Analysis enables a deeper understanding of the causal mechanisms underlying these relationships, offering novel insights into how investments in human capital translate into sustainable development outcomes.

Furthermore, BNA's capacity to model uncertainty and nonlinear relationships is particularly relevant to policy-making in complex, uncertain environments, where understanding causality is paramount to designing effective interventions. By employing this approach, the study aligns with the methodological advances recommended in recent literature (Pearl, 2009; Chen & Pollino, 2012; QS, n.d.) and provides a robust foundation for exploring the interplay between human capital and sustainability.

## Research Results

Flexiplots (see Figure 1) are used before Bayesian Network Analysis (BNA) to explore the distributions, variability, and interactions among the Human Capital Index (HCI) and its key proxies – the components of the Social Progress Index (SPI). This preliminary step is descriptive and reported separately from the Bayesian network results. Importantly, HCI is used here only for exploratory visualisation (2022 cross-section) and is not included as a node in the BNA networks reported below. These visualisations provide insights into potential relationships and dependencies, helping to identify patterns that inform the structure of the Bayesian Network. Additionally, flexplates enable the detection of data anomalies and ensure that critical variables are appropriately scaled, enhancing the reliability of the BNA.

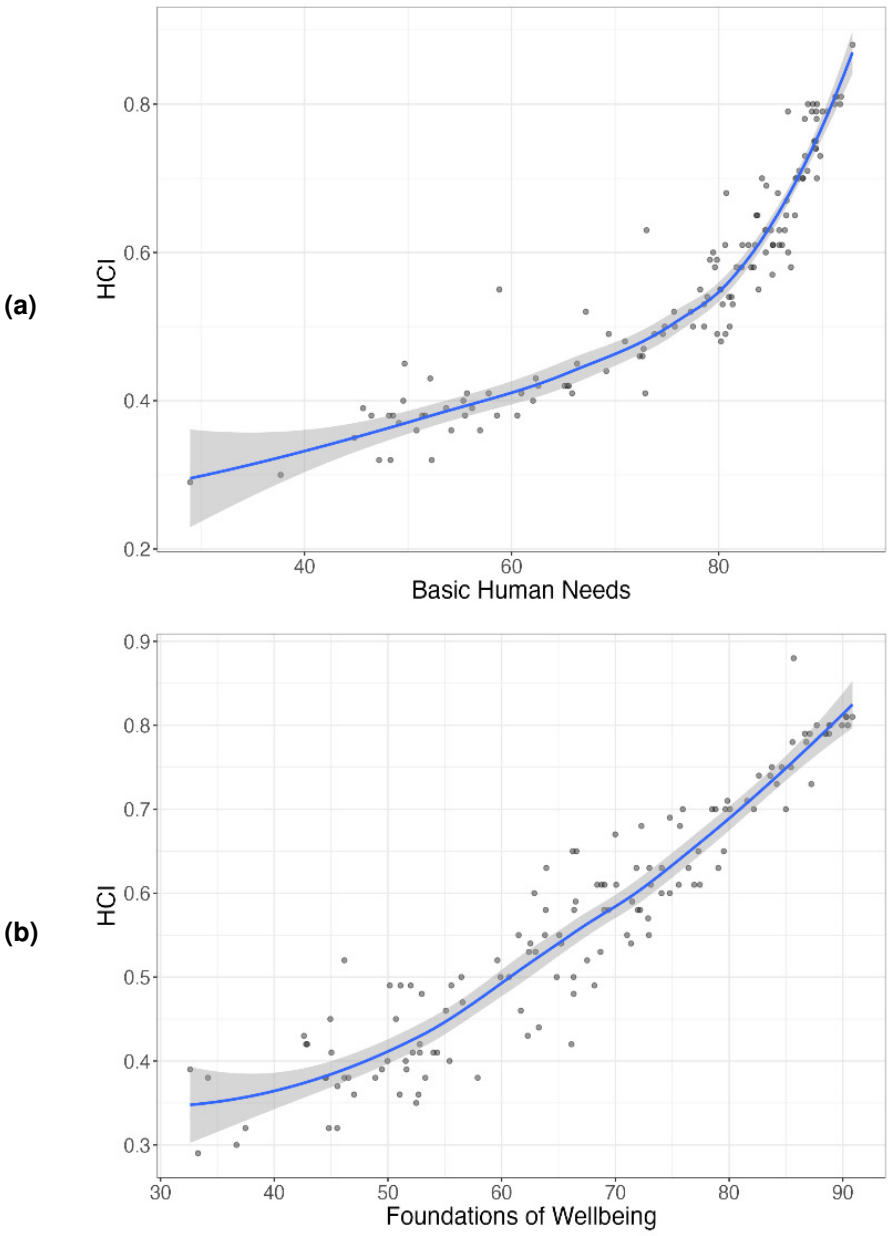
The flexiplot (Figure 1a) shows a positive, nonlinear association between the Human Capital Index (HCI) and Basic Human Needs across 170 countries in 2022. As shown in the flexiplot (Figure 1), higher Basic Human Needs are associated with greater HCI values, suggesting that better access to essential resources such as food, water, and healthcare contributes to stronger human capital outcomes. The curve exhibits diminishing returns at lower levels of Basic Human Needs, where initial improvements yield only moderate gains. However, the trend steepens at higher levels of Basic Human Needs, indicating accelerated growth, likely driven by synergistic advances in health, education, and economic participation. Observations cluster in the upper ranges of Basic Human Needs and HCI, suggesting substantial progress in many regions. Sparse data at lower levels of Basic Human Needs reflect limited instances of unmet need, revealing significant disparities in resource access and development.

The relationship (Figure 1b) between HCI and Foundations of Wellbeing exhibits a similar positive, nonlinear trend. Foundations of Wellbeing focuses on access to education, environmental quality, and health systems, all of which are critical drivers of human capital. As Foundations of Wellbeing increases, HCI improves, reinforcing the importance of comprehensive well-being in human capital development. Incremental improvements at lower levels of Foundations of Wellbeing produce gradual HCI gains, whereas higher levels lead to accelerated growth, emphasizing the compounding effects of advanced well-being factors. Data points are concentrated in the middle to higher ranges of Foundations of Wellbeing and HCI, indicating overall progress. However, the lower range shows greater variability, reflecting disparities in well-being across some regions.

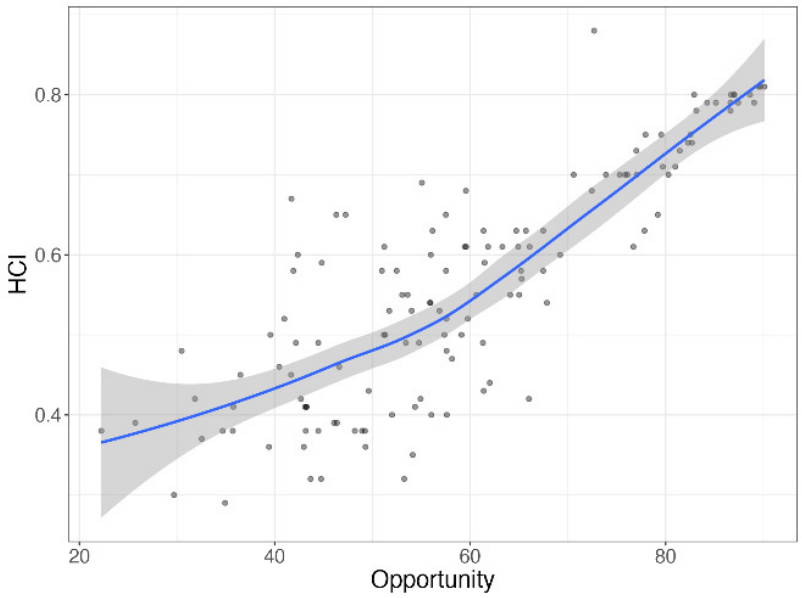
The relationship between HCI and Opportunity (Figure 1c) exhibits a positive, nonlinear pattern. Opportunity represents equitable access to education, personal rights, and inclusivity. Higher Opportunity scores are associated with higher HCI values, emphasizing the role of equity in fostering human capital.

*Figure 1*

**Flexiplots: HCI and Components of SPI**



(c)




Source: authors' calculations based on data from Sustainable Development Solutions Network (n.d.) and Social Progress Imperative (n.d.).

The steepening curve at higher Opportunity levels suggests that societal inclusivity and access to rights accelerate human capital development, producing substantial gains. Wider confidence intervals at lower Opportunity levels indicate greater uncertainty or disparities in HCI outcomes when inclusivity and equity are lacking.

The comparative analysis of Basic Human Needs, Foundations of Wellbeing, and Opportunity underscores their collective importance in shaping human capital. While all three dimensions show positive nonlinear trends, Basic Human Needs underpin early gains, Foundations of Wellbeing compound benefits, and Opportunity drives inclusivity and equity.

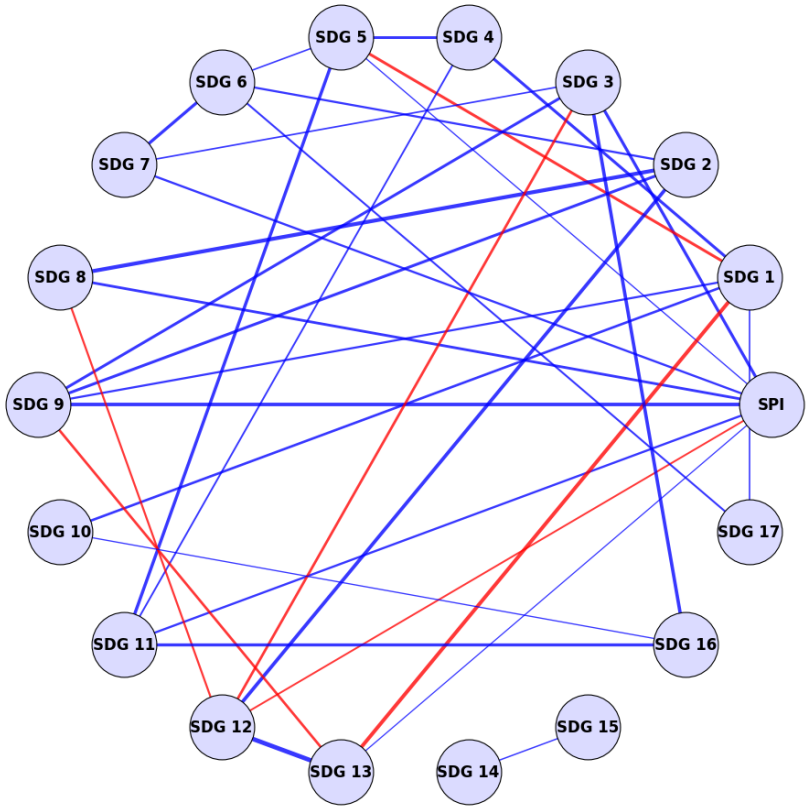
These findings highlight the need for integrated, context-specific strategies to maximize human capital outcomes, address disparities, and leverage opportunities for sustained growth.

The Bayesian network analysis of the Social Progress Index (SPI) and Sustainable Development Goals (SDGs) revealed fundamental interactions and structural properties. The network, comprising 18 nodes (SPI and SDGs 1–17), had a sparsity of 0.725, with 42 significant edges out of 153 possible connections. This relatively sparse structure underscores selective relationships between the SPI and specific SDGs.

The SPI exhibited strong positive associations with Goal 3 (Health), Goal 11 (Sustainable Cities and Communities), and Goal 7 (Affordable and Clean Energy). A negative association with Goal 12 (Responsible Consumption and Production) highlights potential trade-offs between social progress and sustainability practices. Other notable connections included those between Goal 1 (No Poverty) and Goal 6 (Clean Water and Sanitation), and between Goal 8 (Decent Work and Economic Growth) and Goal 9 (Industry, Innovation, and Infrastructure), reflecting systemic interdependencies (Figure 2).

*Figure 2*

**BNA: SPI and SDGs**

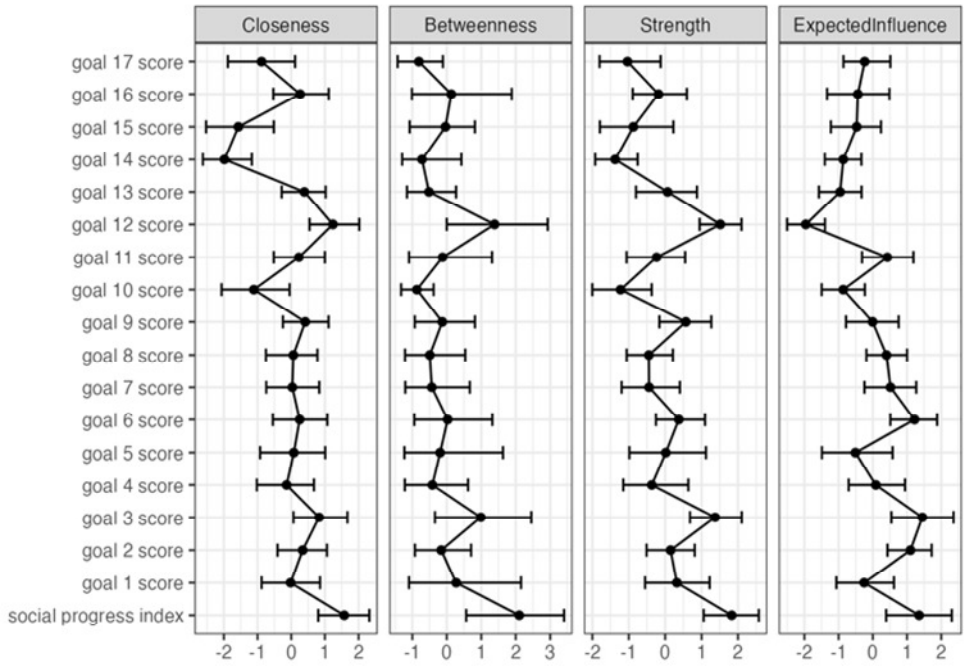



Note: Edge width indicates strength of connections (red – negative, blue – positive), edge weight – |w| ≥ 0.15.
Source: authors' calculations.

Centrality measures (see Figure 3) positioned SPI as a pivotal node within the network, with high betweenness and strength scores.

*Figure 3*

**Centrality measures for Bayesian network SPI and SDGs**



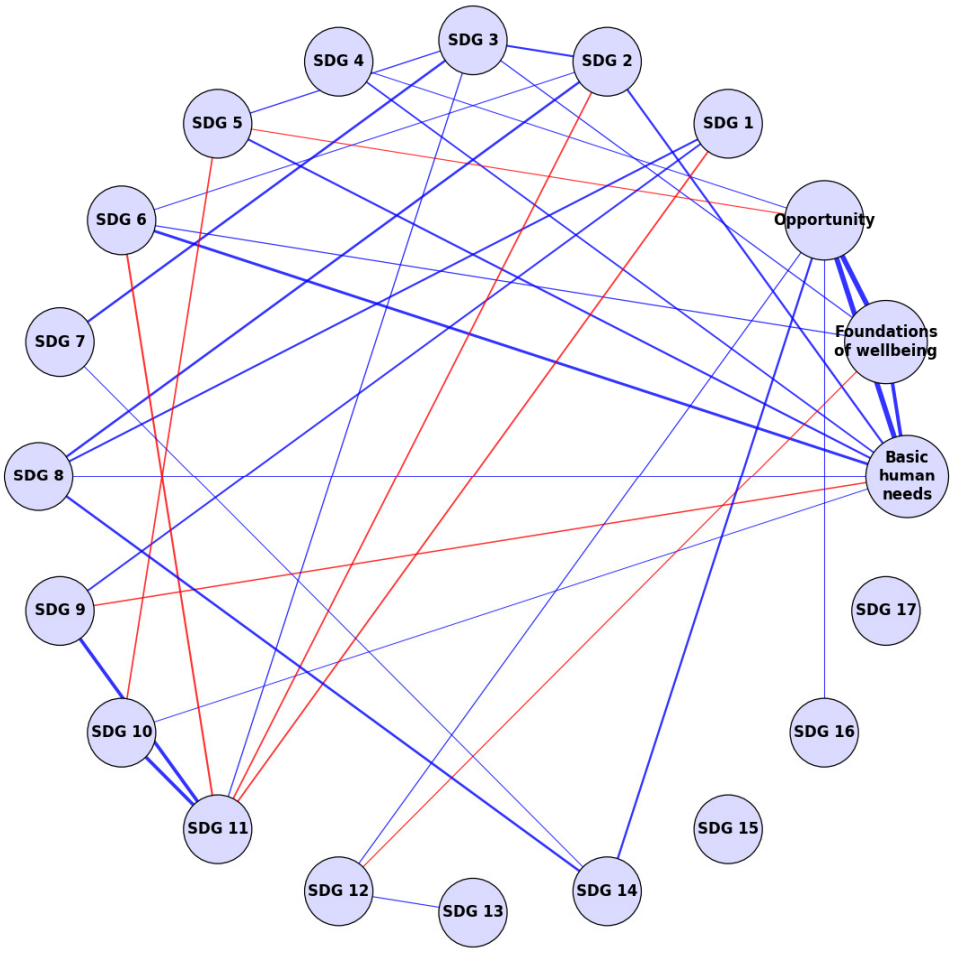

Source: authors' calculations.

Goals 3, 11, and 7 also emerged as influential, whereas Goal 12 demonstrated strong centrality despite its conflicting relationship with SPI. The edge evidence probabilities reinforced the reliability of connections between SPI and critical SDGs, including Goals 3 and 11, with probabilities exceeding 0.9.

Expanding the network to include SPI components (Basic Human Needs, Foundations of Wellbeing, and Opportunity) alongside the SDGs increased the node count to 20, yielding a sparsity of 0.758, with 46 significant edges out of 190 possible connections. This structure (Figure 4) emphasizes the nuanced roles of SPI dimensions in driving SDG progress.

*Figure 4*

**BNA components of SPI and SDGs**



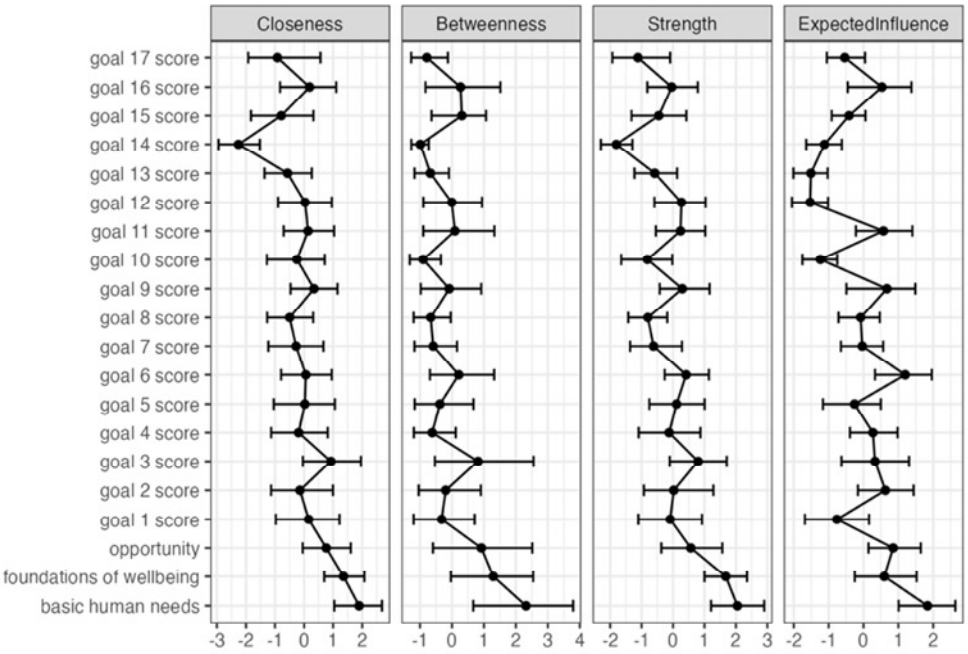

Note: edge width indicates strength of connections (red – negative, blue – positive), edge weight – |w| ≥ 0.10.
Source: authors' calculations.

Basic Human Needs showed robust connections with Goal 3 (Health) and Goal 10 (Reduced Inequalities), underscoring its foundational role in meeting essential human needs. Foundations of Wellbeing is closely linked to Goal 2 (Zero Hunger) and Goal 12 (Responsible Consumption and Production), underscoring the interplay between sustainable resource use and social outcomes. The Opportunity component demonstrates strong links to Goal 4 (Quality Education) and Goal 8 (Decent Work and Economic Growth), emphasizing the importance of education and economic inclusion in fostering social progress.

Centrality analysis (Figure 5) identified Basic Human Needs and Foundations of Wellbeing as key drivers within the network, with high closeness and strength scores.

*Figure 5*

**Centrality measures for Bayesian network SPI components and SDGs**




Source: authors' calculations.

However, negative associations, such as between Foundations of Wellbeing and Goal 12, indicate areas requiring strategic alignment to mitigate trade-offs. The probability of critical edges, such as between Basic Human Needs and Goal 3, exceeded 0.9, indicating solid and reliable associations.

The main hubs in the Bayesian networks for SPI and SDGs, as well as SPI components that influence SDGs, are identified using centrality metrics and network influence. These hubs represent critical nodes that bridge multiple goals and facilitate systemic interactions. Below, we summarize (Table 1) the key hubs, their roles, and their significance in each network.

*Table 1*

**Main Hubs in SPI and SDG Networks**

| Network | Main Hubs | Key Roles | Significance |
|---|---|---|---|
| SPI and SDGs | Social Progress Index (SPI) | Central hub bridging multiple SDGs, especially Goals 3, 7, and 11. | Facilitates systemic progress and drives overall alignment with SDGs. |
| | Goal 3 (Health) | Strongly linked to SPI and Goals 8, 9, and 11. | Acts as a key driver of human development and systemic improvements. |
| | Goal 11 (Sustainable Cities) | Strong connections with SPI and Goals 6 and 9. | Central to urban sustainability and broader social progress. |
| | Goal 12 (Responsible Consumption and Production) | Negative interaction with SPI, but influential in balancing sustainability efforts. | Highlights trade-offs between sustainable consumption and social progress. |
| SPI Components and SDGs | Basic Human Needs | Strongly linked to Goals 3 and 10, foundational to human equity and well-being. | Primary driver for addressing essential human requirements. |
| | Foundations of Wellbeing | Connected to Goals 2 and 12, emphasizing resource sustainability and social outcomes. | Balances resource-related trade-offs while advancing well-being. |
| | Goal 4 (Quality Education) | Key connections with Opportunity and Goal 8, fostering human capital and economic development. | Catalyst for systemic progress across multiple SDGs. |
| | Goal 8 (Decent Work and Economic Growth) | Linked to SPI components and Goals 9 and 4, representing economic development dimensions. | Critical for fostering sustainable economic systems. |

Source: authors' elaboration.

The identified hubs in the networks highlight the strategic nodes at which interventions can have the greatest impact on the Sustainable Development Goals (SDGs). Human Capital (proxied by SPI) emerges as a central driver in the SPI and SDG networks, reflecting its role in bridging multiple SDGs, with Goals 3, 11, and 7 acting as critical supporting hubs. However, trade-offs, such as the negative association with Goal 12, underline the need for policies that balance sustainability and social progress.

In the SPI components and SDG network, foundational dimensions such as Basic Human Needs and Foundations of Wellbeing stand out as primary drivers, emphasizing the critical role of addressing essential human requirements and sustainable resource management. Additionally, Goals 4 (Education) and 8 (Economic Growth) underscore the importance of human capital development and economic inclusivity in advancing broader social progress. These findings provide policymakers with actionable insights to target high-impact areas and optimize interventions across interconnected goals.

Comparing the two networks showed that the SPI network offered a broad overview of social progress and its direct connections with the SDGs. Meanwhile, the SPI components network provided more detailed insights into how specific aspects of the SPI relate to individual SDGs. Notably, health (Goal 3), education (Goal 4), and economic growth (Goal 8) appeared as common focus points across both networks, with implications for prioritizing interventions.

The analysis highlights critical areas for policy focus, including maximizing synergies between the SPI and the SDGs, addressing trade-offs (for example, with Goal 12), and leveraging central nodes like the SPI and its components to optimize progress toward the SDGs.

From the perspective of the SPI components (Table 2), Basic Human Needs**,** Foundations of Wellbeing**,** and Opportunity each play distinct and critical roles in shaping the Sustainable Development Goals (SDGs). The table below summarizes the critical SDGs impacted by each component and highlights their significance in advancing sustainable development.

As seen above, Human Capital influences all aspects of sustainable development. While its direct impact on SDGs such as health (SDG 3) and education (SDG 4) is evident, its indirect effects on goals like responsible consumption (SDG 12) and climate action (SDG 13) underscore its cross-cutting role. For instance, individuals with higher levels of education are more likely to adopt sustainable lifestyles, develop environmental technologies, and advocate for policy changes.

In Table 3, we highlight key nodes from both networks and illustrate their systemic interactions. In the SPI and SDG network, SPI is the overarching influencer, integrating multiple dimensions of social progress.

*Table 2*

**Impact of SPI Components on SDGs**

| SPI Component | Key SDGs Impacted |
|---|---|
| Basic Human Needs | – **Goal 3 (Health)**: Positive impact on healthcare access and outcomes. |
| | – **Goal 6 (Clean Water and Sanitation)**: Supports access to safe water systems. |
| | – **Goal 10 (Reduced Inequalities)**: Addresses disparities by ensuring basic needs. |
| Foundations of Wellbeing | – **Goal 2 (Zero Hunger)**: Supports sustainable food systems. |
| | – **Goal 12 (Responsible Consumption and Production)**: Drives efficient resource use. |
| | – **Goal 4 (Quality Education)**: Facilitates access to knowledge and skill-building. |
| Opportunity | – **Goal 8 (Decent Work and Economic Growth)**: Enhances workforce participation. |
| | – **Goal 5 (Gender Equality)**: Promotes equal opportunities across genders. |
| | – **Goal 4 (Quality Education)**: Strong influence on advanced education and skills. |

Source: authors' elaboration.

*Table 3*

**Most Influential Nodes in SPI and SPI Component Networks**

| Network | Influential Node | Reason for Influence | Implications for Policy and Action |
|---|---|---|---|
| SPI and SDGs | Social Progress Index (SPI) | High betweenness, strength, and closeness centrality. Connects strongly to Goals 3 (Health), 7 (Energy), and 11 (Sustainable Cities). | Acts as an overarching driver of social progress, requiring holistic investments across multiple SDGs. |
| | Goal 3 (Health) | Strong connections to SPI and other goals like Goal 8 (Economic Growth) and Goal 9 (Innovation). | Prioritizing health systems enhances overall human capital, impacting economic and infrastructural development. |

| Network | Influential Node | Reason for Influence | Implications for Policy and Action |
|---|---|---|---|
| | Goal 11 (Sustainable Cities) | Influential in urban sustainability, linking to SPI and Goals 6 (Water) and 9. | Promotes urban planning and infrastructure as key drivers of sustainable development. |
| | Goal 12 (Responsible Consumption) | High centrality despite a negative link to SPI, indicating trade-offs in sustainability efforts. | Policies must balance economic growth with sustainability to address potential conflicts with SDGs. |
| SPI Components and SDGs | Basic Human Needs | Strong connections to Goals 3 (Health), 6 (Water), and 10 (Reduced Inequalities). | Foundational to ensuring equity and addressing essential human requirements. |
| | Foundations of Wellbeing | Links to Goals 2 (Zero Hunger) and 12 (Sustainable Consumption), emphasizing sustainability and resource use. | Policies should ensure environmental sustainability while advancing human development. |
| | Opportunity | Connected to Goals 4 (Education) and 8 (Economic Growth), highlighting its role in inclusivity and skill-building. | Investments in education and economic participation amplify equitable development and innovation. |
| | Goal 4 (Quality Education) | Affects multiple SPI components and connects to Goals 5 (Gender Equality) and 8. | Enhances long-term human capital development through targeted educational policies. |

Source: authors' elaboration.

In the SPI Component network, Basic Human Needs stands out as the foundation for addressing essential disparities. Meanwhile, Foundations of Wellbeing emphasizes resource sustainability, and Opportunity drives inclusivity through education and economic participation. These findings align with previous literature while revealing necessary trade-offs and systemic interdependencies.

The Bayesian networks reveal key nodes, including SPI, Goal 3 (Health), and Goal 11 (Sustainable Cities and Communities), hubs for systemic progress. These findings confirm the foundational role of health and urban sustainability in driving broader development outcomes, as highlighted by previous studies (Lu-

cas, 1988; Sachs et al., 2018). For example, Goal 3 demonstrates strong connections to other SDGs, such as Goal 8 (Decent Work and Economic Growth) and Goal 10 (Reduced Inequalities), underscoring the critical role of health systems in enabling equitable economic growth and social progress. Incorporating SPI components – Basic Human Needs, Foundations of Wellbeing, and Opportunity – reveals more profound insights into their interactions with specific SDGs. Basic Human Needs shows robust connections to Goals 3 (Health) and 10 (Reduced Inequalities), underscoring the centrality of addressing essential needs to enhance social equity and human development. Similarly, the Opportunity dimension shows significant ties to Goals 4 (Quality Education) and 8 (Decent Work and Economic Growth), emphasizing the importance of education and inclusivity in fostering sustainable progress, consistent with studies by Barro and Lee (2013) and Porter et al. (2017).

Our analysis identifies critical trade-offs, such as the negative association between the Foundations of Wellbeing and Goal 12 (Responsible Consumption and Production). This finding reflects the tension between advancing human wellbeing and ensuring sustainable resource use, a challenge acknowledged in prior literature (Nathaniel, 2021). Addressing these trade-offs requires integrated policies that balance short-term gains in social progress with long-term sustainability objectives.

The application of Bayesian networks allowed the exploration of probabilistic causal relationships, offering unique insights beyond traditional correlation-based methods. For example, the solid probabilistic links between the SPI components and Goal 8 (Decent Work and Economic Growth) and Goal 4 (Quality Education) highlight the structural dependencies that drive inclusive growth and innovation. This methodological approach aligns with calls in the literature for data-driven frameworks that can uncover causal pathways in complex socio-economic systems (Pearl, 2009; Chen & Pollino, 2012).

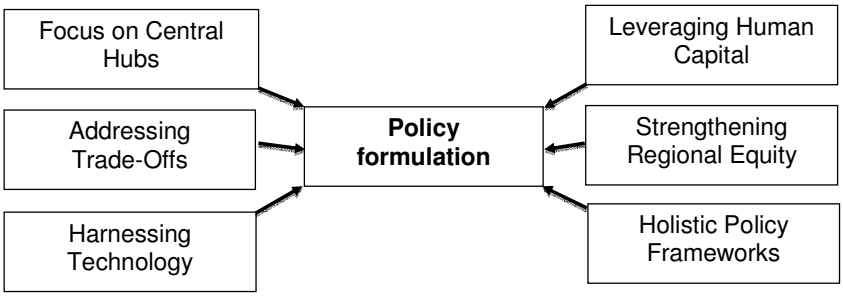
## Discussion

The findings offer actionable insights for policymakers and stakeholders seeking to align human capital investments with sustainable development objectives (Figure 6):

1. Focus on Central Hubs. Identifying critical nodes such as Goal 3 (Health), Goal 11 (Sustainable Cities and Communities), and the SPI highlights strategic areas for intervention. Investments in health systems, urban planning, and social infrastructure can have cascading effects across multiple SDGs, enabling systemic progress. This aligns with previous findings emphasizing the centrality of health and urban equity in development (Sachs et al., 2018; Şentürk et al., 2023).

*Figure 6*

**Practical guidelines for policy formulation to align human capital investments with sustainable development goals**




Source: authors' elaboration.

2. Addressing Trade-Offs. The trade-offs between the Foundations of Wellbeing and Goal 12 (Responsible Consumption and Production) underscore the need for integrated policies that mitigate resource consumption while promoting social outcomes. As Porter et al. (2017) suggest, embedding sustainability education within health and social programs can help balance these priorities.

3. Leveraging Human Capital for Economic Resilience. The strong links between Opportunity, Goal 4 (Quality Education), and Goal 8 (Decent Work and Economic Growth) underscore the importance of fostering education and inclusivity. These findings echo Barro and Lee (2013), who highlighted the role of education in driving innovation and economic productivity. Policymakers must align education policies with market needs to optimize human capital's contribution to economic growth.

4. Strengthening Regional Equity. The results highlight disparities in human capital development across regions, suggesting a need for targeted interventions in underserved areas. Investments in basic human needs, such as healthcare and education, can reduce inequalities and ensure equitable progress across SDGs (Nathaniel, 2021).

5. Harnessing Technology for Human Development. Bayesian analysis underscores the dynamic nature of human capital. Investments in digital education and telemedicine can enhance access to resources in remote and underserved regions, amplifying the impact of interventions on health and education outcomes. This recommendation aligns with Kraay's (2019) emphasis on the role of adaptive technologies in strengthening human capital systems.

6. Holistic Policy Frameworks. The interconnected nature of SPI components and SDGs underscores the need for integrated policy approaches. Multi-

dimensional strategies addressing education, health, and sustainable resource use can create synergies that accelerate progress toward sustainability goals, as demonstrated by Lucas (1988) and Sachs et al. (2018).

The interdependence of SPI components underscores the need for integrated development frameworks under unified strategies which foster cross-sectoral collaboration among government agencies, nongovernmental organizations, and international bodies.

## Conclusions

This article uses Bayesian network analysis (BNA) to investigate the complex causal relationships between human capital and the Sustainable Development Goals (SDGs). Using the Social Progress Index (SPI) and its components as proxies for human capital and SDG metrics, the findings provide a comprehensive view of how investments in education, health, and inclusivity contribute to sustainable development.

The analysis highlights the pivotal role of key hubs, such as health (SDG 3), education (SDG 4), and economic growth (SDG 8), in driving progress across multiple goals. SPI and its components, particularly Basic Human Needs, Foundations of Wellbeing, and Opportunity, emerge as central drivers of systemic development, reinforcing the interconnectedness of human capital and sustainability. At the same time, the study identifies critical trade-offs, such as those between social progress and sustainable resource use, emphasizing the need for integrated approaches to balance competing priorities.

Our results underscore the importance of focusing on critical areas such as health, education, and economic inclusion while addressing structural inequalities to ensure equitable progress. Our research provides actionable insights for designing policies that address the interdependencies and complexities of global challenges. By adopting this integrated and systemic approach, stakeholders can unlock the full potential of human capital to drive equitable and sustainable progress.

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