Available online at www.sciencedirect.com

ScienceDirect

Procedia Computer Science 270 (2025) 4431–4440

Procedia Computer Science

www.elsevier.com/locate/procedia

29th International Conference on Knowledge-Based and Intelligent Information & Engineering Systems (KES 2025)

Reasoning over Interrupted Trends in Systemic Shocks: A Logic-Driven ITSA and Clustering Analysis of Human Development Disruption

Marcus Vinicius Leite[a]*, Jair Minoro Abe[a], Leandro Cigano de Souza Thomas[a], Vando Aparecido Monteiro[a], Irenilza de Alencar Nääs[a], Marcelo Tsuguio Okano[a]

[a] *Graduate Program in Production Engineering-Paulista University-UNIP, Rua Dr. Bacelar, 1212-São Paulo-SP-04026002, Brazil*

Abstract

Understanding how global systemic shocks disrupt long-term development trajectories requires more than economic indicators—it demands a multidimensional perspective grounded in human capabilities and structural resilience. The COVID-19 pandemic has disrupted key dimensions of human development worldwide, amplifying pre-existing inequalities and challenging national capacities to sustain progress in health, education, and income. While numerous studies have examined how countries with different Human Development Index (HDI) levels responded to the pandemic, few have investigated the inverse: how the pandemic itself disrupted the HDI. This gap exists in part due to the limited availability of post-pandemic data until recent years. This study addresses that gap by analyzing how the COVID-19 crisis affected the evolution of HDI across the 15 countries with the highest GDP between 2012 and 2022. We apply Interrupted Time Series Analysis (ITSA) and K-means clustering to detect structural breaks in national HDI trajectories and to classify countries into behavioral profiles based on their post-pandemic recovery patterns. The analysis isolates the impact on each HDI component —life expectancy, expected and mean years of schooling, and gross national income per capita— and identifies five distinct clusters: resilient growth, rapid recovery, slow recovery, stagnation, and sustained decline. The integrated ITSA's and K-means logic-based structure supports causal reasoning under temporal disruption, enabling interpretable cross-country comparisons. The findings highlight the uneven nature of human development recovery and underscore the value of reasoning-driven approaches for policy design under uncertainty and systemic shock. This work contributes to scientific understanding of development resilience by demonstrating how logic-based temporal analysis and structured reasoning techniques can be applied to quantify and interpret systemic disruptions in human development, and supports societal efforts aligned with the UN Sustainable Development Goals, particularly SDG 3 (Health), SDG 4 (Education), and SDG 10 (Reduced Inequalities).

* Corresponding author.
E-mail address: marcus.leite@gmail.com

1877-0509 © 2025 The Authors. Published by Elsevier B.V.

10.1016/j.procs.2025.09.568

Keywords: Human Development Index (HDI), COVID-19 Pandemic, Systemic Shocks, Interrupted Time Series Analysis (ITSA), K-means Clustering, Structural Breaks, Public Policy and Crisis Response, Socioeconomic Recovery, Reasoning-Based Analytical Framework

1. Introduction

Human development is a systemic and multidimensional concept centered on the expansion of individual freedoms and capabilities. The Human Development Index (HDI), developed by the United Nations Development Programme (UNDP), reflects progress in three interrelated dimensions—health, education (measured by expected and mean years of schooling), and income (adjusted for purchasing power parity)—and serves both as a metric and as a policy guide for inclusive and sustainable development [1, 2, 3, 5]. By using normalized indices and a geometric mean, the HDI balances scale differences across dimensions. Though originally proposed as an alternative to GDP per capita, it has become a global benchmark for long-term wellbeing, with expanded versions like the Inequality-adjusted HDI (IDHAD), the Gender Development Index (GDI), and the Augmented Human Development Index (AHDI), addressing inequality and demographic disparities [3, 5, 8]. While robust, the HDI evolves slowly: education and life expectancy respond to long-term structural conditions, and income, though more volatile, is smoothed to reduce short-term shocks. Even minor annual variations may reflect meaningful shifts in national development. This multidimensional structure also makes the HDI valuable for assessing how systemic crises disrupt foundational pillars of wellbeing [7, 11].

The COVID-19 pandemic represents a rare systemic shock with the potential to cause measurable discontinuities in HDI trajectories. By overwhelming public health systems, disrupting education through unequal access to remote learning, and triggering widespread income losses, the crisis exposed and intensified pre-existing socioeconomic vulnerabilities—particularly among marginalized groups such as the poor, elderly, and disabled [10, 12, 15]. Global supply chains were interrupted, entire sectors like tourism and aviation collapsed, and over 1.7 billion students faced educational disruption, many without digital access [13, 16]. These compounding effects destabilized essential services and livelihoods, revealing how health, education, and income—core dimensions of human development—are deeply interdependent and collectively vulnerable in the face of global crises. [13, 14, 15].

While prior studies have analyzed how countries with different HDI levels responded to the pandemic, few have examined how the pandemic itself disrupted HDI evolution [9, 10, 13]. Despite the scale of this disruption, there remains limited empirical understanding of its lasting effects. This gap can be attributed both to the proximity of the event—which has constrained the availability of post-pandemic data and delayed more systematic assessments—and to the HDI's structural inertia, which slows its responsiveness to short-term shocks. This context highlights the need for analytical models that can not only detect disruption but also interpret heterogeneous responses through structured and transparent reasoning.

To take up this challenge, we apply a logic-driven framework to examine whether the pandemic merely delayed development—or fundamentally altered its course. Our study addresses that gap by asking: To what extent did the COVID-19 pandemic introduce measurable discontinuities in human development across the world's largest economies? We propose four working hypotheses: H_1: The pandemic introduced structural breaks in HDI trajectories, affecting both level and growth rate; H_2: The magnitude and direction of disruption varied across countries, producing distinct recovery patterns observable via clustering; H_3: The pandemic's impact was asymmetric across HDI components, with life expectancy and income more affected than education; H_4: Countries with higher pre-pandemic HDI levels tended to show greater resilience or faster recovery, due to stronger institutions and infrastructure.

To test these hypotheses, we examine the 15 countries with the highest GDP using a data-driven approach that integrates Interrupted Time Series Analysis (ITSA) and K-means clustering. This framework supports interpretable causal reasoning under uncertainty, revealing both structural shocks and differentiated recovery paths [2, 4]. This study contributes to the growing field of reasoning-based approaches by integrating inferential logic and unsupervised learning to analyze disruptions across the Human Development Index dimensions. By treating HDI as a dynamic outcome rather than a static indicator, it advances the empirical understanding of development resilience under systemic shocks. Moreover, the study offers actionable insights for public policy, reinforcing the relevance of logic-driven analysis in addressing multidimensional vulnerabilities and supporting progress toward SDG 3 (Health), SDG 4 (Education), and SDG 10 (Reduced Inequalities).

This paper is organized as follows: the Background reviews key concepts and methods; Materials and Methods details the dataset and modeling approach; Results presents the findings from ITSA and clustering; Discussion interprets these considering the hypotheses; and Conclusion reflects on the contributions and future research.

2. Background

Periods of global stress tend to reveal what steady progress often conceals: the complexity of human development, its dependence on underlying structures, and its uneven capacity to respond to large-scale shocks. The HDI remains a critical tool for understanding development as the interplay of interdependent conditions. Its multidimensional structure is particularly relevant for assessing how global crises disrupt health, education, and income—the core pillars of human wellbeing. Through the lens of the HDI, it becomes possible to understand the nature of systemic crises and their socioeconomic effects, such as those observed during the COVID-19 pandemic. However, to make such an observation, it is necessary to adopt analytical approaches capable of understanding disruption.

Interrupted Time Series Analysis (ITSA) is a regression-based method used to evaluate whether a discrete event alters the trajectory of a time-dependent variable. It compares pre- and post-intervention trends to estimate both immediate (level) and gradual (slope) changes, requiring at least three observations before and after the intervention. ITSA can be integrated with other designs such as randomized controlled trials (RCTs) and controlled before-and-after studies (CBAs), and its validity may be enhanced through stratified analysis or complementary data sources [17].

Widely used in the health and social sciences, ITSA is particularly valuable when randomized trials are not feasible or ethically acceptable [17, 27]. It has been applied to evaluate public policies, health campaigns, and economic shocks, supporting causal reasoning by isolating the effect of interventions from ongoing secular trends [28]. Common applications include the assessment of epidemic containment strategies, macroeconomic fluctuations, and regulatory interventions. The standard model involves four key components: the baseline trend, the interruption point, any immediate level change, and a shift in the post-intervention slope—allowing for both absolute and relative interpretation of the intervention's impact [26, 27]. Estimation is typically performed using Ordinary Least Squares (OLS), which minimizes residuals to fit linear models to continuous outcomes in time series [26].

In the context of this study, ITSA enables us to assess whether the COVID-19 pandemic introduced measurable disruptions in HDI trajectories, both in magnitude and direction, offering a robust statistical basis for interpreting long-term developmental impacts.

3. Materials and Methods

This exploratory study used quantitative methods to assess the impact of the COVID-19 pandemic on human development in the 15 countries with the highest GDP. To test our hypotheses, we combined ITSA and K-means clustering, —selected for their robustness and their capacity to support structured reasoning under systemic uncertainty. ITSA, in particular, is well suited to capturing temporal discontinuities caused by external shocks, while clustering enables typological insight into heterogeneous recovery dynamics across diverse development baselines.

The analysis followed four stages: (1) selection of data sources, (2) application of ITSA to detect structural breaks in HDI and its components, (3) clustering of countries based on response patterns, and (4) comparative analysis of recovery groups. GDP rankings for 2022 were drawn from the World Bank's World Development Indicators [2], while HDI data (1990–2022) came from the UNDP's Human Development Reports [1]. These sources provided a reliable basis for cross-national analysis. ITSA was applied to each country from 2012 to 2022, with 2020 as the defined intervention point. We modeled HDI and its components—life expectancy, expected and mean years of schooling, and GNI per capita—using Ordinary Least Squares regression, comparing pre- and post-pandemic trends to estimate changes in level and slope. K-means clustering was then used to group countries based on HDI variation between 2019 and 2022. Normalized variables ensured comparability, and the elbow method determined the optimal number of clusters [3, 4]. In the final stage, we conducted a comparative analysis of HDI trajectories within each cluster, complemented by examination of sub-indicators. We interpreted these patterns in light of socioeconomic and institutional contexts and contrasted them with existing literature to reinforce analytical depth.

Together, ITSA and clustering formed a reasoning-based framework for interpreting both structural disruption and cross-national variation in human development under systemic stress.

4. Results

The historical analysis of HDI trends shows that, before the COVID-19 pandemic, the 15 highest-GDP countries generally followed trajectories of growth or stability, supported by improvements in living conditions, education, and income. Disruptions became evident in 2020, with recovery patterns varying significantly across countries (table 1) [14].

Table 1. HDI Trajectories Before and After the COVID-19 Outbreak in the 15 Largest Economies.

Country	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Australia	0,931	0,929	0,931	0,933	0,936	0,937	0,941	0,941	0,948	0,949	0,946
Brazil	0,732	0,750	0,753	0,752	0,753	0,758	0,762	0,764	0,758	0,756	0,760
Canada	0,921	0,923	0,925	0,927	0,928	0,929	0,930	0,932	0,928	0,934	0,935
China	0,715	0,723	0,732	0,741	0,749	0,757	0,766	0,775	0,781	0,785	0,788
France	0,885	0,888	0,892	0,893	0,896	0,899	0,903	0,905	0,900	0,906	0,910
Germany	0,937	0,938	0,942	0,941	0,941	0,944	0,946	0,951	0,948	0,948	0,950
India	0,594	0,600	0,611	0,619	0,630	0,636	0,636	0,638	0,638	0,633	0,644
Italy	0,881	0,880	0,882	0,881	0,886	0,889	0,894	0,899	0,892	0,899	0,906
Japan	0,906	0,909	0,910	0,913	0,914	0,916	0,917	0,918	0,917	0,920	0,920
Korea (Republic of)	0,897	0,902	0,906	0,908	0,912	0,915	0,918	0,922	0,922	0,926	0,929
Mexico	0,760	0,761	0,765	0,769	0,773	0,776	0,779	0,781	0,757	0,757	0,781
Russian Federation	0,811	0,816	0,818	0,823	0,826	0,827	0,836	0,839	0,826	0,818	0,821
Spain	0,875	0,880	0,884	0,889	0,894	0,896	0,899	0,904	0,894	0,904	0,911
United Kingdom	0,910	0,923	0,924	0,923	0,926	0,929	0,928	0,933	0,920	0,931	0,940
United States	0,920	0,922	0,923	0,924	0,926	0,928	0,930	0,933	0,923	0,921	0,927

China and India exhibited strong pre-pandemic growth, while Brazil, Russia, and Spain advanced more unevenly. South Korea, Mexico, the UK, and France maintained steady progress, and mature welfare states like Italy, the US, Japan, Germany, Canada, and Australia showed consistent increases. Volatility in Brazil, India, Mexico, and the UK reflected internal instability, while Germany, France, Japan, and China displayed greater continuity, suggesting institutional resilience [1, 3, 10].

ITSA revealed varying impacts and recovery trajectories from the COVID-19 pandemic across countries. Prior to the pandemic, most nations exhibited moderate HDI growth, with China and India standing out due to their robust upward trends. In the first year of the pandemic, most countries experienced sharp declines in HDI—except for Australia, Germany, Italy, Japan, South Korea, Canada, and China, which managed to maintain or even improve their scores. In the post-pandemic period, some countries recovered quickly, while others—such as Brazil, the United States, and Russia—faced slow and incomplete recoveries.

Table 2. Estimated ITSA Coefficients for HDI Trajectories in the 15 Highest-GDP Countries (2012–2022).

	Intercept		Pre-Intervention Slope		Intervention Effect		Post-Intervention Slope	
Country	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value	Coefficient	P-value
Australia	0,9070	< 0,05	0,0018	< 0,05	0,0057	< 0,05	-0,0028	< 0,05
Brazil	0,6976	< 0,05	0,0036	< 0,05	-0,0121	0,065	-0,0026	0,465
Canada	0,9038	< 0,05	0,0015	< 0,05	-0,0047	< 0,05	0,0020	< 0,05
China	0,6123	< 0,05	0,0085	< 0,05	-0,0020	< 0,05	-0,0050	< 0,05
Germany	0,9159	< 0,05	0,0017	< 0,05	-0,0025	0,241	-0,0007	0,570
Spain	0,8276	< 0,05	0,0040	< 0,05	-0,0138	< 0,05	0,0045	< 0,05
France	0,8510	< 0,05	0,0028	< 0,05	-0,0076	< 0,05	0,0022	< 0,05
United Kingdom	0,8869	< 0,05	0,0024	< 0,05	-0,0151	< 0,05	0,0076	< 0,05
India	0,5146	< 0,05	0,0068	< 0,05	-0,0159	< 0,05	-0,0038	0,323
Italy	0,8455	< 0,05	0,0026	< 0,05	-0,0064	0,083	0,0044	0,056
Japan	0,8865	< 0,05	0,0017	< 0,05	-0,0030	< 0,05	-0,0002	0,742
Korea (Republic of)	0,8572	< 0,05	0,0034	< 0,05	-0,0032	< 0,05	0,0001	0,853
Mexico	0,7199	< 0,05	0,0033	< 0,05	-0,0322	< 0,05	0,0087	< 0,05
Russian Federation	0,7643	< 0,05	0,0039	< 0,05	-0,0178	< 0,05	-0,0064	< 0,05
United States	0,8984	< 0,05	0,0018	< 0,05	-0,0120	< 0,05	0,0002	0,821

Table 2 presents the key coefficients used to compare HDI trends before and after the pandemic. These include the Initial Intercept, representing the HDI value at the beginning of the time series; the Pre-Intervention Slope, which captures the trend in HDI prior to 2020; the Intervention Effect, indicating the immediate change in level associated with the onset of the pandemic; and the Post-Intervention Slope, reflecting the rate of change in HDI following the intervention period. The ITSA analysis revealed that the pandemic had a direct negative impact on the HDI in 2020 in nearly all the countries studied, with some continuing to face difficulties in the following years.

The results also clearly indicated a heterogeneous recovery trend. Recovery varied significantly across countries: while some returned to pre-pandemic HDI levels—or even surpassed them by 2022—others continued to experience persistent challenges. The ITSA analysis also revealed a wide range of behaviors and trajectories among the countries studied, both before and after the pandemic (Fig 1a, 2a, 3a, 4a, 5a).

To better understand these differences and identify common patterns, a cluster analysis was performed. This technique made it possible to group the countries into five distinct clusters, each characterized by similar features and dynamics in terms of HDI evolution and its components throughout the analyzed period.

Table 3. Clustered Country Profiles Based on HDI Variation During the COVID-19 Period.

Cluster	Cluster Member Characteristics	Countries	HDI 2019	HDI 2022	HDI Δ 2022–2019
Resilient Growth	Refers to countries that consistently maintained or increased their HDI, demonstrating a remarkable capacity for adaptation	China	0,775	0,788	0,013
Rapid Recovery and Growth	Includes countries that, after an initial decline, quickly recovered their HDI levels and surpassed pre-pandemic values.	India	0,638	0,644	0,006
		Italy	0,899	0,906	0,007
		Korea (Republic of)	0,922	0,929	0,007
		Spain	0,904	0,911	0,007
		United Kingdom	0,933	0,940	0,007
Slow Recovery and Growth	Comprises countries that, despite a slower recovery, still achieved some degree of progress.	Australia	0,941	0,946	0,005
		Canada	0,932	0,935	0,003
		France	0,905	0,910	0,005
		Germany	0,951	0,950	-0,001
		Japan	0,918	0,920	0,002
		Mexico	0,781	0,781	0,000
Slow Recovery and Stagnation	Describes countries that experienced a delayed recovery and failed to return to pre-pandemic HDI levels, remaining stagnant.	Brazil	0,764	0,760	-0,004
		United States	0,933	0,927	-0,006
Overall Declining Trends	Includes countries that suffered significant declines in HDI during the pandemic and have not achieved substantial recovery, remaining below pre-pandemic levels.	Russian Federation	0,839	0,821	-0,018

Based on the different trajectories observed across the countries analyzed, five classification clusters were defined. Table 3 presents these clusters along with the countries assigned to each group, their HDI value in the last year before the pandemic, the most recent HDI value available at the time of this study, and the difference between the two [4].

4.1. Cluster of Countries with Resilient HDI Growth

China stands out as the only country in the Cluster of Countries with Resilient HDI Growth. It sustained and even improved its HDI during the pandemic, driven by swift containment policies, strong government economic support, and an efficient health system (Fig. 1a). These efforts were bolstered by high public trust in the central government, which enabled widespread compliance with control measures and a 95% vaccination rate [9, 23, 24]. The ITSA analysis confirmed gains in life expectancy and gross national income per capita, with minimal pandemic-related disruption (Fig. 1c). Population growth also supported internal demand, strengthening China's role in the post-pandemic global economy [2, 25]. Educational indicators, however, remained stagnant due to school closures and remote learning challenges. Still, China recorded a 1.68% HDI increase over pre-pandemic levels, reflecting economic recovery and effective social policies [9, 14].

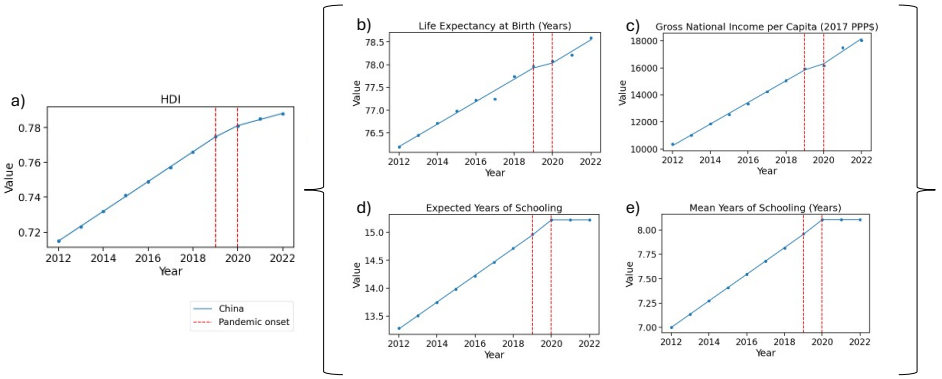

Fig. 1. Evolution of the HDI and its components in Countries with Resilient HDI Growth. (a) HDI; (b) Life Expectancy at Birth in Years; (c) Gross National Income per Capita in 2017 PPP$; (d) Expected Years of Schooling; (e) Mean Years of Schooling.

A diversified economy, strong healthcare system, and coordinated government response were central to this sustained progress [9, 23, 24].

4.2. Cluster of Countries with Rapid HDI Recovery and Growth

South Korea, Spain, India, Italy, and the United Kingdom form the Cluster of Countries with Rapid HDI Recovery and Growth.

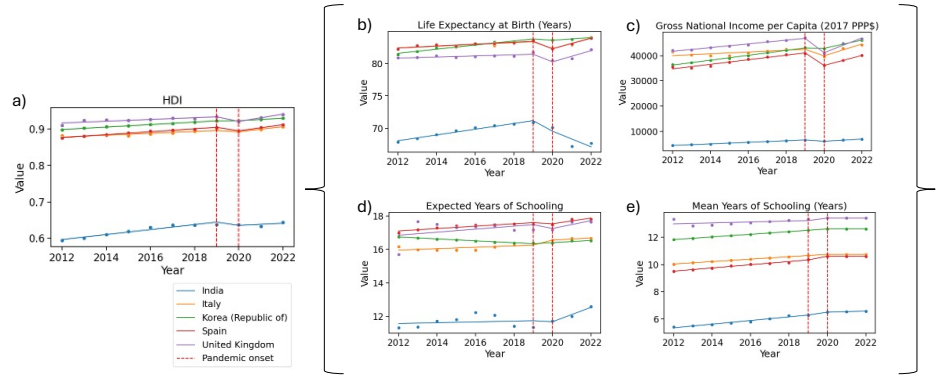

Fig. 2. Evolution of the HDI and its components in Countries with Rapid HDI Recovery and Growth. (a) HDI; (b) Life Expectancy at Birth in Years; (c) Gross National Income per Capita in 2017 PPP$; (d) Expected Years of Schooling; (e) Mean Years of Schooling.

After significant initial impacts, all countries—except South Korea, which stagnated briefly—recovered quickly and exceeded pre-pandemic HDI levels (Fig. 2a) [24]. This recovery was supported by effective government actions, including lockdowns, mass testing, and high vaccination rates [9]. Italy and Spain led in immunization, the UK performed well despite a more moderate approach, and India used digital tools to support healthcare monitoring and social recovery [23, 24]. Life expectancy improved across the group, except in India, where high mortality offset gains despite strong vaccine uptake (Fig. 2b) [9]. Italy's early vaccination rollout and Spain's high coverage—backed by strong government action—reduced mortality, while the UK lagged slightly but still outperformed most peers [23, 24]. Education indicators also improved, particularly in South Korea and India, where remote learning and digital infrastructure minimized disruption. Economically, all countries—except India—showed strong recovery. The UK maintained growth throughout the pandemic, reflecting its economic resilience [9, 21].

The combination of effective health measures, adaptive educational strategies, and economic strength was essential to the remarkable HDI growth observed in these countries, as confirmed by the ITSA results.

4.3. Cluster of Countries with Slow HDI Recovery and Growth

Australia, Canada, France, Germany, Japan, and Mexico comprise the Cluster of Countries with Slow HDI Recovery and Growth. Although initially impacted by the pandemic, all eventually exceeded pre-pandemic HDI levels. Mexico had the steepest early decline but began recovering in 2021, with strong growth in 2022. Australia remained stable in 2020, declined in 2021, and then rebounded, highlighting the effectiveness of its health and economic policies (Fig. 8) [8]. Canada, France, Germany, and Japan also exhibited slow but steady HDI recovery, supported by stimulus programs, mass vaccination, and health system reforms. By the end of 2022, all had surpassed pre-pandemic HDI levels (Fig. 8). ITSA results showed life expectancy dropped sharply in Mexico and France, while Australia saw an unusual increase, reflecting strong healthcare resilience. Canada, Germany, and Japan maintained relative stability; in Japan, demographic pressures intensified COVID-19 mortality among older adults [20]. Australia, France, and Germany all achieved high vaccination rates through robust government action [8, 9, 23, 24].

In education, most countries maintained stable performance, except Mexico, which faced declines in expected years of schooling due to school closures and limited remote access. Germany reported emotional challenges among youth, though less severe than in Italy or Spain [22].

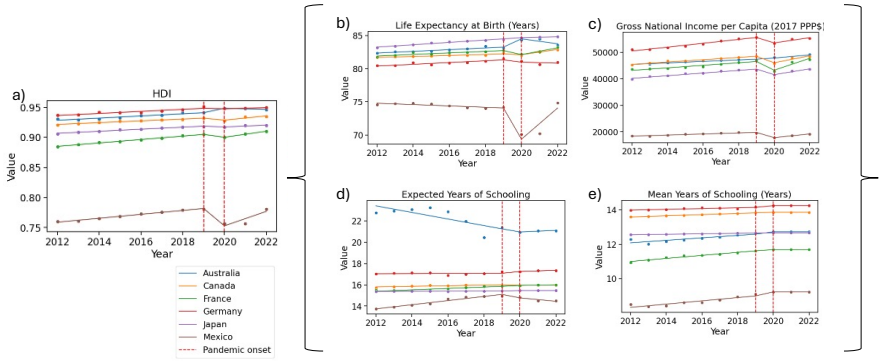

Fig. 3. Evolution of the HDI and its components in Countries with Slow HDI Recovery and Growth. (a) HDI; (b) Life Expectancy at Birth in Years; (c) Gross National Income per Capita in 2017 PPP$; (d) Expected Years of Schooling; (e) Mean Years of Schooling.

Australia reversed a pre-pandemic educational decline, while Mexico showed notable recovery in mean years of schooling (Fig. 3d, 3e). Economically, most countries struggled, except Australia, which increased its growth rate, reflecting effective crisis management [21]. Overall, this group illustrates the need for targeted, multidimensional policies to recover and advance human development in the wake of global shocks.

4.4. Cluster of Countries with Slow HDI Recovery and Stagnation

Brazil and the United States form the Cluster of Countries with Slow HDI Recovery and Stagnation. Both experienced two consecutive years of decline and failed to return to pre-pandemic HDI levels. In Brazil, limited policy coordination, weak compliance with quarantine, and an already strained health system led to high mortality and broader setbacks. In the U.S., a fragmented response and economic disruption further impeded recovery (Fig. 4a) [9, 20, 21].

ITSA revealed sharp life expectancy declines in both countries. In the U.S., it fell nearly 5% with only a 2% rebound. In Brazil, the 4% drop saw minimal recovery by 2022 (Fig. 4b). Delayed vaccination and inconsistent messaging contributed to Brazil's outcome, while vaccine hesitancy played a key role in the U.S. [9, 23, 24].

In education, Brazil recovered quickly in expected years of schooling after a moderate decline, while the U.S. continued to see losses in this indicator, despite stable mean years—suggesting some systemic resilience. Both countries faced psychosocial impacts among youth due to isolation measures, prompting targeted responses, especially in Brazil [22] (Fig. 4d, 4e). Economically, both endured severe disruptions.

The U.S. faced a downturn on par with the Great Depression but later exceeded pre-pandemic GDP levels, thanks to structural economic strength [21]. Brazil also rebounded, eventually surpassing its pre-crisis economic performance (Fig. 4b).

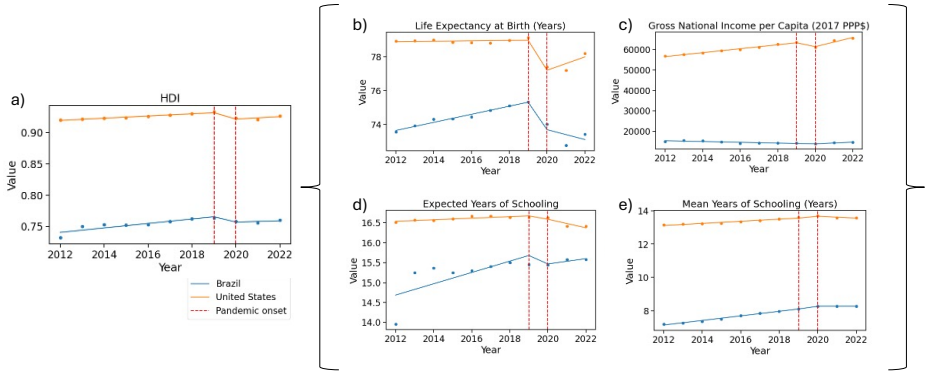

Fig. 4. Evolution of the HDI and its components in Countries with Slow HDI Recovery and Stagnation. (a) HDI; (b) Life Expectancy at Birth in Years; (c) Gross National Income per Capita in 2017 PPP$; (d) Expected Years of Schooling; (e) Mean Years of Schooling.

These results emphasize the importance of coordinated public health responses and reveal the complex, multidimensional pathways involved in human development recovery.

4.5. Cluster of Countries with Overall Declining Trends

Russia, the only country in the Cluster of Countries with Declining HDI Trends, saw its HDI drop for two consecutive years, falling below 2016 levels despite signs of recovery in 2022 (Fig. 5a). This decline stemmed from delayed quarantine measures and logistical issues that worsened virus transmission and strained public health.

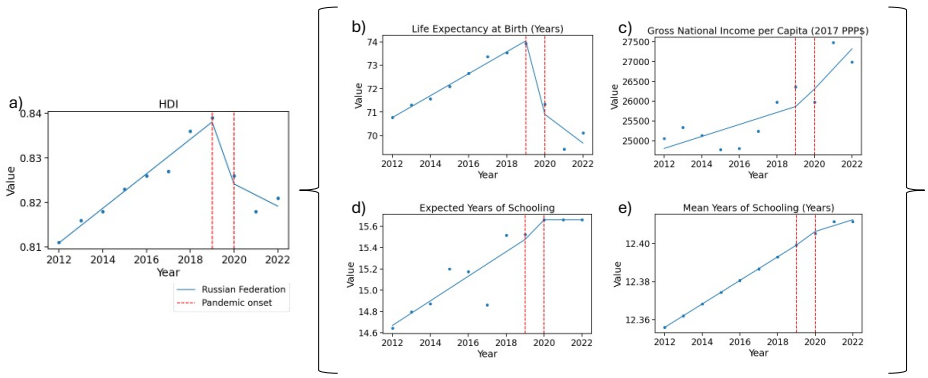

Fig. 5. Evolution of the HDI and its components in Countries with Overall Declining Trends. (a) HDI; (b) Life Expectancy at Birth in Years; (c) Gross National Income per Capita in 2017 PPP$; (d) Expected Years of Schooling; (e) Mean Years of Schooling.

Pre-existing demographic pressures, including population decline and high mortality among older adults [20], were compounded by economic reliance on oil and gas exports, which suffered during the global downturn [21]. The healthcare system faced severe strain, with hospitals in multiple regions reaching full capacity, delaying not only COVID-19 treatment but also care for other medical conditions. This directly impacted life expectancy, which saw its sharpest decline in over a decade—falling by nearly five years, a 7% reduction that brought it below 2012 levels (Fig. 5b). The pandemic disrupted formal education in Russia, particularly in rural areas, leading to declines in expected years of schooling. In contrast, GNI per capita followed a divergent path: after falling in 2020 to 2018 levels, it rebounded sharply in 2021—marking the strongest growth in over a decade. This was fueled by rising global oil and gas prices and domestic economic adjustments (Fig. 5d, 5e).

Despite efforts to recover in 2022, Russia's HDI trajectory remains below previous levels, highlighting the scale of the crisis and the urgent need for reforms in healthcare and economic policy. It illustrates how prolonged pandemic effects and policy choices shape long-term human development.

5. Discussion

The findings of this study support and refine the four proposed hypotheses. ITSA and clustering revealed structural breaks and divergent HDI recovery paths, offering insight into resilience and vulnerability under systemic stress.

H_1 was confirmed: the pandemic disrupted HDI trajectories, with China and India showing strong pre-crisis growth, while Brazil and Russia were more volatile. Spain, Mexico, and the UK recovered quickly; the U.S. and Brazil stagnated. H_2 was validated through clustering, which identified five recovery patterns. China maintained growth, while Russia faced continued decline—highlighting contrasting institutional responses. H_3 confirmed asymmetric impacts across HDI components. Life expectancy fell sharply in the U.S., Brazil, and Russia—linked in part to vaccine hesitancy [9, 23, 24]. GNI per capita rebounded in China and Russia, while education remained more stable, with improvements in South Korea and India and declines in Mexico and the U.S. [14]. H_4 was partially supported. Germany, Australia, and Canada recovered steadily, while the U.S. stagnated despite a high HDI. China grew consistently, underscoring that resilience depends more on institutional strength and policy coordination than initial HDI level.

In sum, the pandemic caused measurable disruption and uneven recovery. Coordinated responses in countries like Italy and Spain aided recovery, while fragmented approaches in Brazil and the U.S. prolonged disruption. Lasting consequences—including long COVID, worsened health outcomes, and growing inequality—likely extend beyond what HDI captures, especially in data-poor settings [15]. Resilience is shaped not only by economic capacity, but by governance, public trust, and sustained investment in human development.

6. Conclusion

This study examined how the COVID-19 pandemic affected HDI trajectories in the 15 countries with the highest GDP. Using ITSA and clustering, we analyzed structural breaks and post-crisis recovery patterns from 2012 to 2022 across HDI components—life expectancy, education, and income—within a reasoning-based analytical framework.

Findings confirmed that the pandemic introduced measurable disruptions in most countries, with wide variation in recovery paths. Five behavioral clusters emerged, from resilient growth (e.g., China) to prolonged decline (e.g., Russia), shaped by institutional responses, public trust, and systemic capacity. Life expectancy was the most affected, while income and education showed mixed resilience.

By treating HDI as a dynamic outcome, this study offers a novel contribution to the analysis of systemic shocks. The integration of ITSA and clustering enabled meaningful interpretation of disruption and heterogeneity across national contexts, reaffirming the value of logic-driven methods for understanding complex development stressors.

Results highlight that early, science-based responses helped preserve broader human development outcomes. Crucially, high pre-pandemic HDI did not guarantee resilience—what mattered was how effectively countries mobilized institutional and social capacity. These insights may assist policymakers in designing development strategies that are both adaptive and resilient, particularly under global stress scenarios. More broadly, the study underscores the value of logic-based analytical approaches in informing multidimensional policy decisions during complex crises.

Limitations include the use of national-level data, which may obscure subnational disparities, and the likelihood that longer-term consequences (e.g., long COVID, deferred care) are not yet fully visible. Data gaps also remain in countries with weaker statistical systems.

Future research should explore subnational trends, integrate governance and behavioral variables, and examine institutional learning and public perception. These dimensions could strengthen the explanatory scope of reasoning-based models in future crises.

As systemic risks intensify, human development will continue to face external shocks. This study underscores the need for analytical tools capable not only of detecting disruption, but of explaining how and why it unfolds—and how it can be mitigated.

References

[1] United Nations. Human Development Index – Human Development Reports [Internet]. New York: UNDP; [no date]. Available from: https://hdr.undp.org/data-center/human-development-index

[2] World Bank. GDP ranking. World Development Indicators. Washington, DC: The World Bank; 2024. Available from: https://datacatalog.worldbank.org/search/dataset/0038130/gdp_ranking

[3] Ferraz D, Mariano EB, Rebelatto D, Hartmann D. Linking Human Development and the Financial Responsibility of Regions: Combined Index Proposals Using Methods from Data Envelopment Analysis. Social Indicators Research. 2020;150(2):439–478. doi: 10.1007/s11205-020-02338-3

[4] Krüger JJ. Comment on "A new clustering approach using data envelopment analysis". European Journal of Operational Research. 2010;206(1):269–270. doi: 10.1016/j.ejor.2010.02.023

[5] Booysen F. An overview and evaluation of composite indices of development. Social Indicators Research. 2002;59(2):115–151. doi: 10.1023/A:1016275505152

[6] Mariano EB, Ferraz D, Gobbo SCO. The Human Development Index with Multiple Data Envelopment Analysis Approaches: A Comparative Evaluation Using Social Network Analysis. Social Indicators Research. 2021;157(2):443–500. doi: 10.1007/s11205-021-02660-4

[7] Herre B, Arriagada P. The Human Development Index and related indices: what they are and what we can learn from them. Our World in Data; 2023. Available from: https://ourworldindata.org/human-development-index

[8] Kondo T, et al. Report on the nature, characteristics, and outcomes of the Japanese healthcare system. Global Health & Medicine. 2022;4(1):37–44.

[9] Lazarus JV, et al. A global survey of potential acceptance of a COVID-19 vaccine. Nature Medicine. 2021;27(2):225–228.

[10] Nicola M, Alsafi Z, Sohrabi C, Kerwan A, Al-Jabir A, Iosifidis C, et al. The socio-economic implications of the coronavirus pandemic (COVID-19): A review. International Journal of Surgery. 2020;78:185–193. doi: 10.1016/j.ijsu.2020.04.018

[11] Feriyanto N. The effect of employment, economic growth, and investment on HDI: In provinces in Indonesia. Journal of Economics, Business & Accountancy Ventura. 2016;19(1):1.

[12] Goyal M, Singh P, Singh K, Shekhar S, Agrawal N, Misra S. The effect of the COVID-19 pandemic on maternal health due to delay in seeking health care: Experience from a tertiary center. International Journal of Gynecology & Obstetrics. 2021;152(2):231–235.

[13] Zhou L, Puthenkalam JJ. Effects of the Human Development Index on COVID-19 Mortality Rates in High-Income Countries. European Journal of Development Studies. 2022;2(3):26–31.

[14] Pokhrel S, Chhetri R. A literature review on impact of COVID-19 pandemic on teaching and learning. Higher Education for the Future. 2021;8(1):133–141.

[15] Aburto JM, Schöley J, Kashnitsky I, Zhang L, Rahal C, Missov TI, et al. Quantifying impacts of the COVID-19 pandemic through life-expectancy losses: a population-level study of 29 countries. International Journal of Epidemiology. 2022;51(1):63–74. doi: 10.1093/ije/dyab207

[16] Bhan S, Julka A. Disability inclusive COVID-19 response: best practices [Internet]. New Delhi: UNESCO Office in New Delhi; 2021. 48 p. Report No.: 2021/IN/SHS/100. Available from: https://unesdoc.unesco.org/ark:/48223/pf0000378354

[17] Bernal JL, Cummins S, Gasparrini A. Interrupted time series regression for the evaluation of public health interventions: a tutorial. International Journal of Epidemiology. 2017;46(1):348–355.

[20] Schumacher AE, et al. Global age-sex-specific mortality, life expectancy, and population estimates in 204 countries and territories and 811 subnational locations, 1950–2021, and the impact of the COVID-19 pandemic: a comprehensive demographic analysis for the Global Burden of Disease Study 2021. The Lancet. 2024;403(10440):1989–2056.

[21] Altig D, et al. Economic uncertainty before and during the COVID-19 pandemic. Journal of Public Economics. 2020; 191:104274.

[22] Ravens-Sieberer U, et al. Impact of the COVID-19 pandemic on quality of life and mental health in children and adolescents in Germany. European Child & Adolescent Psychiatry. 2022;31(6):879–889.

[23] Matveeva O, Shabalina S. Comparison of vaccination and booster rates and their impact on excess mortality during the COVID-19 pandemic in European countries. Frontiers in Immunology. 2023;14: Article 1202753.

[24] Araf Y, et al. Omicron variant of SARS-CoV-2: Genomics, transmissibility, and responses to current COVID-19 vaccines. Journal of Medical Virology. 2022;94(5):1825–1832.

[25] Robinson E, et al. A systematic review and meta-analysis of longitudinal cohort studies comparing mental health before versus during the COVID-19 pandemic in 2020. Journal of Affective Disorders. 2022;296:567–576.

[26] Efron B, Hastie T, Johnstone I, Tibshirani R. Least angle regression. Annals of Statistics. 2004;32(2):407–499.

[27] Wagner AK, et al. Segmented regression analysis of interrupted time series studies in medication use research. Journal of Clinical Pharmacy and Therapeutics. 2002;27(4):299–309.

[28] Penfold RB, Zhang F. Use of interrupted time series analysis in evaluating health care quality improvements. Academic Pediatrics. 2013;13(6 Suppl): S38–S44.