Sustainable Development Through Human Capital: Evidence from Korea

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Abstract

This study highlights the significance of human development for both the present and the future, stressing the necessity for sustainable human development across generations. Economic sustainability is often viewed through the lens of intergenerational equity.

The research investigates the relationship between human capital and sustainable development by employing the Error Correction Model (ECM) and the Autoregressive Distributed Lag (ARDL) bounds testing method to analyze both long-term and short-term relationships among these variables.

The empirical evidence indicates a causal relationship between human capital and sustainable development. Human capital is a crucial component in driving innovation and plays a vital role in sustainable development by maximizing utility over an indefinite time horizon.

Keywords: Human capital and sustainable development, Causality, Autoregressive distributed lag(ARDL), Error correction model(ECM).

JEL classifications: C32, Q01, Q56

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1. Introduction

1.1 Definitions of Growth, Development, and Sustainability Concepts

It has been established that there is not one definition of sustainable development (Robinson 2002; Robinson and Herbert 2001), and different people with different cultural backgrounds and priorities have different definitions (Thompson and Rayner 1998). Turner (1988) and O'Riordan (1988) echo Redclift (1987, 1990) in distinguishing between sustainable growth and sustainable development (Huckle 1991).

Sustainable development is used and interpreted in such varied ways that while O'Riordan (1985) called SD a contraction term, Redclift suggests that it may be just another development truism (Redclift 1987), and it is summarized. Most people use sustainable development interchangeably with ecologically sustainable or environmentally sound development (Tolba 1984; Lélé 1991). Weitzman (1997) states that sustainability is a measure of future consumption.

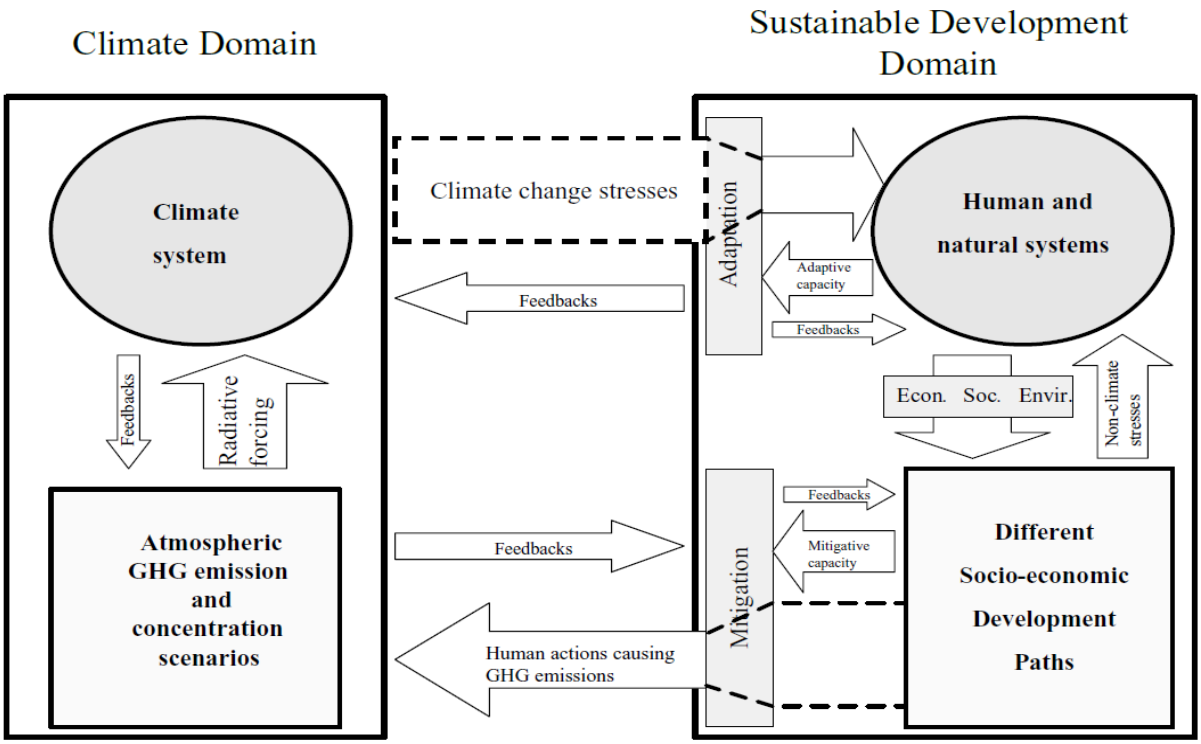


Figure I. Climate change – an integrated framework considering socio-economic development.
Source: IPCC (2001c). https://www.ipcc.ch/report/ar3/syr/
IPCC (2003). https://www.ipcc.ch/site/assets/uploads/2018/03/8.pdf

Figure 1 describes a possible distinction between economic and human sustainability (Porreca 2020). The distinction is a useful reminder that the ultimate objective of sustainability is not human activity, but human beings themselves. The full cycle of cause and effect between climate change and sustainable development is summarized in Figure 1, in which Munasinghe and Swart (1999, 2005) outline an integrated assessment modeling framework (IPCC 2001a, 2001b; Bartelmus 1994a, 1994b; Munasinghe 1999; Sohn 2026).

1-2 Economic Growth

Government policy can cause permanent changes in variables that lead to lasting shifts in growth rates. This contrasts with the neoclassical growth model by Solow (1956), which states

that long-term growth relies mainly on external technological progress. Such differences are clear in both AK and R&D models (Jones 1995).

The AK-style growth models by Romer (1986, 1987), Lucas (1988), and Rebelo (1991) focus on capital accumulation, suggesting that a broad definition of capital can achieve constant returns and foster endogenous growth. In contrast, the R&D-based models from Romer (1990), Grossman and Helpman (1991a, 1991b), and Aghion and Howitt (1992) emphasize technological progress driven by profit-maximizing individuals, which enhances productivity and also contributes to endogenous growth (van Marrewijk, 1999).

As Smith (1776) predicted, intangible assets, especially human capital, constitute the majority of total wealth in most countries. Science and education, along with culture, play a vital role in the development of human capital (HC). HC is regarded as a central component of an innovation-driven economy (Matousek and Tzeremes 2021). There are various definitions of human capital, each attempting to explain this concept through its relationships with different economic parameters (Ali et al. 2018; Rocha et al. 2019; Samans 2017; Zallé 2019; Kulzhanova et al. 2021).

The concept of human capital refers to individuals as significant contributors to economic growth and social development (Anard and Sen 2000). It can be seen as both a means and an end to human welfare and well-being. Additionally, it views the development of human consciousness as the true source of wealth creation (Šlaus and Jacobs 2011).

Human capital can influence growth performance through several channels (Kumar 2006); i) Human capital acts as an input in the production function (Mankiw et al. 1992). ii) The accumulation of human capital creates positive externalities, resulting in increased productivity among individuals, which contributes to endogenous growth (Lucas 1988). iii)

Investing in human capital stimulates greater innovation and research and development (R&D), further driving endogenous growth (Romer 1990; Faucheux et al. 1996). iv) The accumulation of human capital can also affect physical capital investment, leading to a secondary effect on growth performance (Benhabib and Spiegel 1994). v) Additionally, there may be reverse causation, where higher growth rates encourage more schooling and the development of human capital, as found by Bils and Klenow (1998).

An evolutionary growth theory that explains the relationship between human evolution and economic development during various stages has been proposed by Galor and Moav (2002) and later by Galor (2011). This theory highlights the importance of human capital as a key driver of economic growth. Both Lucas (1988) and Romer (1986) emphasized the critical role of human capital in this process, with accumulation being important in determining long-run economic growth. Barro (1999) argued that the accumulation of human capital is a vital component of the development process, which is significantly influenced by public programs in education and health. Schumpeter (1934, 1939) highlighted the importance of adopting innovations, new technologies, and physical capital in fostering economic growth. Furthermore, Mankiw et al. (1992) provided a theoretical framework that supports the central role of human capital in the growth process (Savvides and Stengos 2009).
The purpose of this study is to assess the causal relationship between human capital and sustainable development.

The structure of the paper is organized as follows: Section 2 presents a literature review, Section 3 outlines the methodology, and Section 4 presents the Korean critical control variables,

Section 5 discusses the data, cointegration tests, and hindcast evaluations, while Section 6 presents the empirical results and discussion. Finally, Section 7 concludes the paper with a summary of the key findings.

2. Literature Review

The concept of human capital has a long history in economic thought, tracing back to figures such as Petty (1690), Cantillon (1755), Smith (1776, 1790), Mill (1848), Farr (1853), Engel (1883), and Marshall (1890). Its recognition regained momentum with the works of Schultz (1961), Becker (1964), and Mincer (1974). Human beings and their acquired abilities have been regarded as significant components of national wealth, alongside traditional assets (Folloni and Vittadini 2010; Kiker 1966).

Human capital plays a crucial role in driving growth, sustainable prosperity, and social cohesion (OECD 1998, 2001). According to Manuelli and Seshadri (2014), human capital is central to determining a nation's wealth, and the quality of this human capital varies systematically with the country's level of development. Despite this, Benhabib and Spiegel (1994) found a weak correlation between economic growth and increases in educational attainment, a point further supported by Temple (1999). Romer (1990) and Barro (1999) suggested that human capital plays a crucial role in economic growth by facilitating the adoption of new technologies (Kalaitzidakis et al. 2001). Additionally, Nelson and Phelps

(1966) highlighted the important link between education and economic growth, which has significant implications (Bowlus and Robinson 2012).

How education affects economic growth in 89 countries, using a human capital index from the Penn World Table and World Bank data. Results show that a 0.1 increase in the education index raises real GDP per capita by 0.8 percentage points, with greater benefits in low and middle-income countries. This suggests that these nations should invest more in education to boost economic growth (Bah 2023).

As the full significance of the issues discussed at the environmental conference (UNCED) in Rio in 1992 becomes increasingly apparent, the integration of human progress and environmental conservation has emerged as one of the central challenges facing the modern world (Pronk and Haq 1992; Speth 1992; Brundtland 1993; Anard and Sen 2000).

The structures of physical, human, and social capital limit future production, and wealth is always a result of past activities (Mises 1996). The impact of human capital on economic growth can also be examined through the convergence analysis proposed by Barro and Sala-i-Martin (1992). In this context, Mankiw et al. (1992) developed an extension of the Solow growth model that explicitly includes a process for the accumulation of human capital.

Theoretical foundations regarding the positive relationship between human capital and economic growth can be traced back to seminal papers by Mankiw et al. (1992) and Lucas (1988). On the empirical side, Romer (1989) was one of the first researchers to conduct ad-hoc cross-country regressions analyzing the growth rate of GDP, using a proxy for human capital among the regressors (Middendorf 2006).

Since the early 1960s, human capital has been a central focus of study in economics, both theoretically and empirically. Over the past two decades, the formation of human capital has become a crucial aspect of neoclassical growth theory (Langelett 2002).

A global model may not fully capture the complexities of diverse situations. Local models could provide better insights into specific groups, each with similar relationships between indicators and human capital (HC) (Frühwirth-Schnatter 2006). Sensitivity analysis can be employed to assess how responsive a latent HC model is to changes in parameter values and model structure (Breierova and Choudari 2001; Saltelli 2009). Additionally, appropriate methods must be developed to address missing data issues in latent variable models (Takahiro 2005).

One of the most crucial factors in economic growth is human capital (Lucas 1988; Mankiw et al. 1992; De la Fuente and Cicoone 2002; De la Fuente and Doménech 2000, 2006; Tudorescu 2010). This relationship manifests in two significant ways: first, through its impact on production via labor productivity (Romer 1990; Mankiw et al. 1992), and second, by enhancing competitive advantage through innovation and technology diffusion (Siggel 2000, 2001; Pelinescu 2015).

There is a well-established link between birth rates and investments in education and training, as well as between these investments in human capital and economic progress (Becker 1964). However, we argue that the current system of industrial relations can no longer be assumed to effectively process the environmental changes that influence the development and utilization of human capital (Kochan and Litwin 2011).

As governments focus on the knowledge economy and the value of education, human capital theory is crucial. However, its often technical research can be difficult for policymakers to access and apply (Hartog and Brink 2007).

Malthus (1996) posits that when unchecked, population increases at a geometric rate, while subsistence resources grow only at an arithmetic rate. Galor and Weil (1999, 2000) found that historical evidence indicates that the main event distinguishing the Malthusian and Post-Malthusian eras is the acceleration of technological progress. Additionally, Barro and Lee (1994) argue that, given certain levels of schooling and health, a higher initial real GDP per capita reflects a greater level of physical capital available per person. Furthermore, Tadesse (2007) found that the evidence aligns with the idea that financial development enhances productivity by promoting technological innovations and facilitating their adoption, as it provides access to substantial external capital at lower cost.

In the endogenous growth literature, Aghion and Howitt (1992) identify two perspectives on how human capital influences the growth rate of output: the Nelson and Phelps (1966) approach, known as the NP approach, and the Lucas (1988) approach. The NP approach, which is also supported by Romer (1990) and Aghion and Howitt (1992), posits that human capital is essential for the discovery of new technologies through research and development (R&D). As a consequence, the growth rate of output is dependent on the level of human capital (Cannon 2000).

In their study, Rajan and Zingales (1998) found that countries with more developed financial systems experience superior growth in capital-intensive sectors that heavily rely on external finance. Beck et al. (2000), as well as Fisman and Love (2007), demonstrated that financial development is positively correlated with GDP growth and supports industries with promising growth opportunities. Additionally, Shen (2013) showed that the interaction between dependence on external finance and financial development exhibits diminishing returns as financial development improves. Furthermore, Hermes and Lensink (2003) argued that the development of the financial system enhances the positive relationship between

foreign direct investment (FDI) and economic growth, as supported by Mello and Luiz (1999) and Nair-Reichert and Weinhold (2001).

Ang (2008, 2011) examines the role of financial development in stimulating economic growth and investigates the direction of causality between these two variables. Additionally, Using ARDL bounds and ECM cointegration techniques, Ang (2010) suggests that financial liberalization has the potential to enhance economic growth in Korea[1]. Moreover, Choe and Moosa (1999) find that financial development contributes to real growth in Korea. However, Cho (2001) contends that poorly implemented financial liberalization in Korea has exacerbated the size and pace of the financial crisis in 1997. King and Levine (1993) reignited interest in studying the link between finance and economic growth. They found that financial sector development is strongly related to GDP per capita growth, helping to accumulate physical capital and improve its efficiency in use.

In a specific case, Esso (2010) examined the finance-growth nexus in Korea and found that a long-run relationship exists between the two, but the direction of causality runs in different directions. Weak sustainability posits that welfare can be maintained by substituting manufactured capital for natural capital, though there may be exceptions (Ekins 2014).

The weak instruments (WI) problem is characterized by two key features: i) two-stage least squares (2SLS) is biased compared to ordinary least squares (OLS), and alternatives like limited-information maximum likelihood (LIML) may not fix this, ii) the standard first-order asymptotic distribution is unreliable for inference (Hahn and Hausman 2003).

Multicollinearity in regression analysis arises when there is not enough information to accurately estimate individual parameters. In small samples, it can be acceptable to sacrifice

[1] Hereafter Korea refers to the Republic of Korea (South Korea).

some unbiasedness in ordinary least squares estimators to reduce the mean squared error of key parameters (Feldstein 1973).

Christopoulos and Tsionas (2004) employed panel cointegration and fully modified Ordinary Least Squares (OLS) approaches in a study of 10 developing countries. Their findings established that financial depth has an equilibrium relationship with the real economy, with financial depth also causing GDP growth. Manuelli (2015) emphasizes that human capital is vital for a nation's wealth and varies with development. While no clear link exists between financial deepening and economic growth, it is positively related to GDP growth and inflation volatility, which can increase financial instability due to heightened risk-taking in poorly regulated systems (Sahay et al. 2015).

Yakita (2001) shows that money growth encourages human capital accumulation by shifting asset demand from money to capital and reallocating resources from physical to human capital. Additionally, higher inequality in human capital can reduce the demand for capital goods while enhancing the productivity of inventors (Iacopetta 2010; Tudorescu et al. 2010).

Recent studies highlight the importance of human capital in international growth rates. While education measures are commonly used, they often overlook crucial math and science skills. Recognizing labor quality can enhance our understanding of growth (Hanushek and Kimko 2000). Josten (2000) states that, in a closed economy's steady-state equilibrium, consumption, production, human capital, and physical capital grow at a uniform rate, determined solely by the time private households of different ages invest in education and training.

Gemmell (1996) suggests that larger stocks of human capital may facilitate greater investment in both physical and human capital, while also directly affecting income growth. Krebs (2003) finds that a reduction in uninsurable idiosyncratic labor income risk decreases investment in physical capital but increases investment in human capital, ultimately boosting growth and

welfare. In his study, Gundlach (1995) reveals that the effect of human capital formation on output per worker is twice as significant as the positive impact of physical capital formation.

According to the UNDP's Human Development Reports, human development is defined as the broadening of people's choices (UNDP 1990). Desai (1991) specifically addresses the Human Development Index (HDI), explaining its rationale and potential future revisions. Similarly, Chakravarty (2003) provides an empirical illustration of the axiomatically characterized indices.

Disagreements regarding the naming of our era as the Anthropocene center less on whether it constitutes a new geological epoch - though that remains an important question (Davis 2011; Malin 2021) - and more on its political economy (Moore 2019).

3. Methodology

3.1 Ramsey Function

The standard economic literature on optimal growth originates from Ramsey (1928). In his seminal paper, Ramsey addressed the problem of maximizing the total utility (or welfare) over an infinite time horizon, given specific technology and an initial capital stock. Beckerman and Hepburn (2007) presented the following equation based on Ramsey (1928):

$$r = s = \rho + \mu g \qquad (1)$$

where r is the market interest rate, s is the social rate of time preference, ρ is the pure rate of time preference, μ is the marginal utility elasticity of consumption, and g is the real growth rate of consumption per capita. Furthermore, Fankhauser and Tol (2005) assume that savings rates are determined internally and are influenced by climate change.

In general, Samuelson (1937) demonstrates that marginal utility decreases with income in a monotonic manner. Additionally, Loewenstein and Prelec (1992) indicate that the discounted utility model played a dominant role in the economic analyses of intertemporal choice. Nordhaus (1993) defines utility as the population size [P(t)] multiplied by the utility of per capita consumption u[c(t)]. The resulting utility function is

$$U[c(t), P(t)] = Pt\{[c(t)]^{1-\alpha} - 1\}/(1-\alpha) \quad (2)$$

where α is a measure of the social valuation of different levels of consumption. When α =0, the utility function is linear, and there is no social aversion to inequality. When α =1, the function is a logarithmic or Bernoullian utility function (Bernoulli 1954)

Most of this literature adopts the objective of maximizing an integral over time of the discounted utility flow, represented as $e^{-\rho t}\, u(c_t)$, where c_t is the consumption at time t, $u(c)$ is an increasing and strictly concave function, and $\rho > 0$ is the rate of pure time discount. Thus, the common aim is to maximize this optimality criterion:

$$\int_0^{\infty} e^{-\rho t} u(c_t) \mathrm{dt} \quad (3)$$

subject to certain assumptions regarding the aggregate production function, population growth, and technological progress (Anard and Sen 2000), the analysis conducted by Nelson and Phelps (1966) explores how steady-state production levels are influenced by a country's ability to

adopt technologies. We assume constant efficiency growth at the world frontier, denoted as W, with L and M representing labor growth rates for a given country, *c*, at time *t*.

$$\hat{A}_t^{L,W} = g^L \text{ and, } \hat{A}_t^{M,W} = g^M \quad (4)$$

Each country's human capital (HC), and thereby its capacity to adopt technologies ($\emptyset_c^L$ and $\emptyset_c^M$), is assumed to remain constant over time. In steady state, the efficiency in each country is expected to grow at the same rate as the world frontier (Ciccone and Papaioannou 2009).

Schultz (1975) argues that development depends on entrepreneurs' creativity and innovation. Human capital is essential for fostering innovation and technological progress, serving as the foundation of new growth theories. Moreover, human capital functions not only as a catalyst for growth but also as a productive input alongside labor and physical capital (Schultz 1961). However, modeling the role of human capital in the economic growth process has posed several challenges. The Solow-Swan model of neoclassical growth provides a useful starting point for analyzing the contribution of human capital (Savvides and Stengos 2009).

Sustainable development is a somewhat vague term that was popularized in the Brundtland Commission report (World Commission on Environment and Development (WCED) 1987) but was earlier mentioned in the World Conservation Strategy (International Union for Conservation of Nature (IUCN) 1980). It is generally understood to mean that the well-being of the current generation should not be pursued at the expense of future generations (Barbier et al. 1990). The concept of economic sustainability is rooted in Solow's theories on capital convertibility (Solow 1974, 1986, 1993) and the Hicks-Lindahl concept of maximum income, which suggests saving essential capital resources for the benefit of future generations while implementing a fair distribution among those generations. Economic sustainability aims to

maximize the flow of income and consumption while at least maintaining the stock of assets that generate beneficial outputs (Hicks 1936; Maler 1990).

A standard justification for aggregation is based on the Hicks-Leontief composite commodity theorem (Hicks 1936; Leontief 1936), which states that variables that are perfectly correlated can be aggregated freely (Lewbel 1993).

Phillips and Perron (1988) propose a nonparametric method for controlling serial correlation when testing for a unit root. This study employs the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests to determine the order of integration of the variables. The trace and maximum eigenvalue statistics are estimated using the Johansen cointegration approach. In cases where the trace and maximum eigenvalue statistics yield conflicting results, the choice of which to follow depends on the interpretability of the cointegration relationships (Johansen 1988; Johansen and Juselius 1990).

The accuracy of a Korean hindcast is confirmed using several metrics, including the mean absolute percentage error (MAPE), mean absolute error (MAE), root mean squared error (RMSE), and the Theil inequality coefficient (Makridakis et al. 1998; Fair 1986; Sohn 2019).

This study aims to analyze the relationship between human capital and sustainable development, as well as to evaluate the causal connections among financial development, economic growth, foreign direct investment (FDI), and trade openness in relation to the Human Development Index (HDI) within the Korean economy.

3.2 Time Series Perspective

The decomposition from a time series perspective is formulated as follows:

$$H_t = f(Y_t, F_t, FI_t, TR_t) \quad (5)$$

Here, H_t represents the Human Development Index (HDI), Y_t denotes the real GDP per capita, F_t serves as the financial development proxy measured by real domestic credit per capita, FI_t signifies the real foreign direct investment (FDI) per capita, and TR_t indicates trade openness (exports + imports) per capita at time *t*.

According to the Granger representation theorem, if there exists a cointegration relationship among the variables in the equation, there will be Granger causality in at least one direction, provided that the variables are integrated of order one (Granger 1986). Engle and Granger (1987) caution that applying the Granger causality test in the presence of cointegration may lead to misleading results when using VAR estimation with first-differenced variables. Furthermore, a dynamic ECM can be computed from the ARDL specification through a simple linear transformation, as demonstrated by Alogoskoufis and Smith (1991), Banerjee et al. (1986), Bårdsen (1989), Hassler and Wolters (2006), Maddala and Kim (1998), and Wickens and Breusch (1988).

3.3 Uncertainty

Weitzman (1998, 2001, 2010, 2011) estimated that the appropriate discount rate for the distant future is uncertain, and so it is necessary to establish reasonable discount rates to determine the appropriate time profile of discount factors for each discount rate (Pearce et al. 1990; Filar and Haurie 2010; Traeger 2009, 2014). In addition, Guo et al. (2006) estimate that the shape and speed of decrease in the certainty-equivalent discount rate

depend entirely on the assumed probability distribution of discount rates. Moreover, Gollier (2002, 2013) assumes that the uncertainty of a discount rate is estimated by the current and future uncertainty in the growth rate of consumption, *g*, and that the discount rate scheme depends on the risk aversion parameter estimate. Furthermore, Spackman (2011) assumes that there is uncertainty about the rate even when the future continues to be similar to the past.

Pesaran and Shin (1998) show that the ARDL approach yields consistent long-run coefficient estimates, regardless of the order of integration. To ensure reliability, all variables will be logged before estimating the long-run relationship:

$$\ln H_t = \eta_1 + \eta_2 \ln Y_t + \eta_3 \ln F_t + \eta_4 \ln FI_t + \eta_5 \ln TR_t + \varepsilon_t \quad (6)$$

The human development index (HDI) is denoted as H_t, while η represents the parameter. Y_t denotes real GDP per capita, F_t denotes financial development represented by real domestic credit per capita, FI_t stands for real foreign direct investment (FDI) per capita, TR_t denotes trade openness (exports + imports) per capita, and ε_t is the error term at time *t*. To ensure reliable results, all variables are converted into natural logarithms.

In analyzing the long-run relationships among variables - specifically CO_2 emissions, economic growth, energy use, financial development, FDI, and trade - we employ the ARDL bounds testing approach to cointegration. The model can be represented as follows:

$$\Delta \ln H_t = \alpha_0 + \Sigma_{i=1}^{p} \psi_i \Delta \ln H_{t-i} + \Sigma_{i=1}^{p} \phi_i \Delta \ln F_{t-i} + \Sigma_{i=1}^{p} \varphi_i \Delta \ln Y_{t-i} + \Sigma_{i=1}^{p} \omega_i \Delta \ln FI_{t-i} + \Sigma_{i=1}^{p} \delta_i \Delta \ln TR_{t-i} +$$

$$\theta_H \ln H_{t-1} + \theta_F \ln F_{t-1} + \theta_Y \ln Y_{t-1} + \theta_{FI} \ln FI_{t-1} + \theta_{TR} \ln TR_{t-1} + \varepsilon_{t-1} \quad (7)$$

Here, Δ serves as the first difference operator; α_0 is the parameter, and ψ, ϕ, φ, ω, δ, and ρ represent the short-run parameters. The long-run coefficients are denoted by θ_H, θ_F, θ_Y, θ_{FI},

and θ_{TR}, while ε_t remains the error term at time t. The null hypothesis of no cointegration is stated as H_0: $\theta_H = \theta_F = \theta_Y = \theta_{FI} = \theta_{TR} = 0$. Rejecting the null hypothesis H_1: $\theta_H \neq \theta_F \neq \theta_Y \neq \theta_{FI} \neq \theta_{TR} \neq 0$ indicates the presence of cointegration. The F-statistic is used for this cointegration analysis: if it exceeds the upper critical bound (UCB), it signifies that all variables are I(1), whereas the lower critical bound (LCB) indicates that all variables are I(0). If the F-statistic is below the LCB, no cointegration exists. However, if it lies between the LCB and UCB, the inference remains inconclusive.

To explore causality among the series, we employ the Granger causality test within the vector error correction model (VECM). According to Granger and Weiss (1983), if a pair of I(1) series is cointegrated, causation must exist in at least one direction. The error correction model (ECM) helps analyze long-run relationships, as supported by various studies (Lütkepohl and Saikkonen 1999; Kilian and Lütkepohl 2017; Banerjee and Marcellino 2009; Boswijk 1994, 1995; Garratt et al. 2006; Hassler 2000; Pradel and Rault 2003; Burke and Hunter 2005). The Granger causality test using VECM can be formulated as follows:

$$(1\text{-}A)(H_t, F_t, Y_t, FI_t, TR_t) \tag{8}$$

$$\varphi_i + \Sigma_{i=1}^{p} (1\text{-}A)\, \eta_i\, (H_{t-1}, F_{t-1}, Y_{t-1}, FI_{t-1}, TR_{t-1}) + ECM_{t-1}\phi_i + \lambda_i \tag{9}$$

Here, (1-A) is the difference operator, φ_i (i = 1,…,5) denotes the time-variant constant, η_i (i = 1,…,5) represents the optimal lag length determined by minimizing the Akaike information criterion (AIC), ECM_{t-1} is the lagged residual from the long-run relationship, ϕ_i (i = 1,…,5) is the adjustment coefficient, and λ_i (i = 1,…,5) is the disturbance term, which is assumed to be uncorrelated with a mean of zero.

For bounds testing, AIC is used to determine the optimal lag length for the variables. Research by Lütkepohl (1991, 2005), Judge et al. (1980), Pesaran and Shin (1998), Gonzalo

and Pitarakis (1999), and Hsiao (1979a, 1979b) suggests that AIC lag length criteria yield efficient results.

Additionally, stability tests, as outlined by Brown et al. (1975) and Johnston and DiNardo (1997), are conducted for both short- and long-run coefficients using the cumulative sum (CUSUM) and cumulative sum of squares (CUSUMSQ) tests. These tests are based on recursive residuals to assess the constancy of the regression relationship over time (Ploberger 1989).

4. Korean critical control variables

The Korean critical control variables, such as public education expenditure, R&D investment, and technological innovation, are key drivers of human capital formation and sustainable development as follows.

4.1 Korean government expenditure on education

Galor and Zeira (1993) highlighted that education, although an indivisible investment, yields higher private and social returns than physical capital (Galor 2011). Barro (2000) suggests that inequality does not have a direct effect on growth beyond its effects through education, fertility and investment. Table 1 shows % of GDP: (4.5% (2015), 4.3% (2016), 4.3% (2017), 4.5% (2018), 4.7% (2019), 4.8% (2020), 4.9% (2021)).

Table 1. Korean government expenditure on education

Year	2015	2016	2017	2018	2019	2020	2021
Total % of GDP	4.5	4.3	4.3	4.5	4.7	4.8	4.9

Sources: World Development Indicators (2025). http://www.worldbank.org

4.2 Major R&D Budget Size

The Ministry of Science and ICT (MSIT) announced that it has developed a revision draft of the budget allocation for national R&D projects in 2025 and finalized it at the ninth Presidential Advisory Council on Science and Technology (PACST) deliberation meeting held. The major R&D budget for 2025 is KRW 24.8 trillion, a significant increase from that of the previous year; it includes KRW 24.5 trillion reviewed until June and the amount to be adjusted and reflected after additional revisions until the completion of the government budget plan* in Table 2.

Table 2. Major R&D Budget Size by Year

Year	2023	2024	2025(tentative)*
Key R&D program budget	KRW 24.7 trillion	KRW 21.9 trillion	KRW 24.8 trillion

Source: Ministry of Science and ICT (2024). https://www.msit.go.kr

4.3 Global Innovation Index

Republic of Korea GII Ranking (2020-2024). Table 3 shows the rankings of Korea over the past four years. Data availability and changes to the GII model framework influence year-on-year comparisons of the GII rankings. The statistical confidence interval for the ranking of Korea in the GII 2024 is between ranks 3 and 6. Korea has 4 clusters in the top 100 S&T clusters of the Global Innovation Index.

Table 3. Korea has 4 clusters in the top 100 S&T clusters of the Global Innovation Index.

Year	GII position	Innovation inputs	Innovation outputs
2020	10th	10th	10th

2021	5th	9th	5th
2022	6th	16th	4th
2023	10th	12th	7th
2024	6th	6th	4th

Source: World Intellectual Property Organization (WIPO 2024)
https://www.wipo.int/gii-ranking/en/republic-of-korea

Korea performs better in innovation outputs than in innovation inputs in 2024. This year, Korea ranks 6th in innovation inputs. This position is higher than last year. Korea ranks 4th in innovation outputs. This position is higher than last year (WIPO 2024)

South Korean families are overspending on education, especially private tutoring, driven by labor market changes and an educational "arms race". This trend is exacerbating social and economic issues, leading the country into an "education trap" (Hultberg et al. 2017).

Quality education is vital for fostering innovation. In Korea, the total education spending per tertiary student, including public and private funding, is relatively low, and the student-teacher ratio is high compared to other advanced countries (Lee 2005).

5. Data, cointegration test and hindcast evaluation

5.1 Data

Data were collected from the UNDP Human Development Reports (2024), http://hdr.undp.org, and the World Development Indicators of the World Bank (2025), http://data.worldbank.org/indicator, for the period from 1990 to 2023. The Human Development Index (HDI) is defined as the process of enlarging people's choices

(UNDP 2024). We measure financial development using real domestic credit to the private sector per person as a share of GDP. While this is important, it doesn't fully capture a country's financial health. In frontier and developing Asia, financial inclusion has improved but remains behind emerging markets. Limited access to finance for small and medium enterprises presents an opportunity for greater inclusivity (Dabla-Norris et al. 2015).

Meanwhile, GDP per capita, foreign direct investment (FDI) per capita, and trade openness are measured through exports and imports per capita as a share of GDP. Figures 2 and 3 illustrate these indicators, and all variables are expressed in natural logarithms.

Table 4 presents the descriptive statistics and the correlation matrix. The Jarque-Bera test (1980) indicates that the data follow a normal distribution. The correlation analysis shows a positive correlation among all variables. After establishing the order of integration for the variables, tests for panel cointegration were conducted. The results of the Pedroni tests (1999, 2004) are presented in Table 4 below. These results indicate that the majority of the seven tests for both within and between dimensions confirmed the existence of cointegration among the variables. However, the Panel rho and Group rho tests consistently accepted the null hypothesis of no cointegration. This is not concerning, as a Monte Carlo simulation by Pedroni (2004) demonstrates that these two tests tend to underestimate the rejection of the null hypothesis when the sample sizes (N and T) are small, as is the case in this study. Therefore, it is concluded that a cointegrating relationship exists among the variables.

Table 4. Descriptive statistics and correlation matrix

Variables	$\ln H_t$	$\ln Y_t$	$\ln F_t$	$\ln FI_t$	$\ln TR_t$
Mean	-0.159545	2.869885	2.893100	-2.378931	2.539852
Median	-0.140992	2.971182	3.277349	-2.104575	2.768811
Maximum	-0.073647	3.559795	4.095111	-1.262308	3.442755
Minimum	-0.313342	1.874261	1.210750	-4.342806	1.205971

Std. Dev.	0.072993	0.516438	0.941428	0.887872	0.721909
Skewness	-0.608532	-0.307132	-0.439909	-0.708492	-0.381776
Kurtosis	2.147798	1.781541	1.717722	2.444024	1.671128
Jarque-Bera	3.127280	2.637777	3.425949	3.282348	3.327625
Probability	0.209373	0.267432	0.180329	0.193752	0.189415
lnH_t	1.000000				
lnY_t	0.963478	1.000000			
lnF_t	0.985783	0.977281	1.000000		
lnFI_t	0.567241	0.413593	0.518375	1.000000	
lnTR_t	0.973413	0.975412	0.978235	0.537235	1.000000

Sources: World Development Indicators (2025). http://www.worldbank.org
UNDP-Human Development Report (2024). http://hdr.undp.org

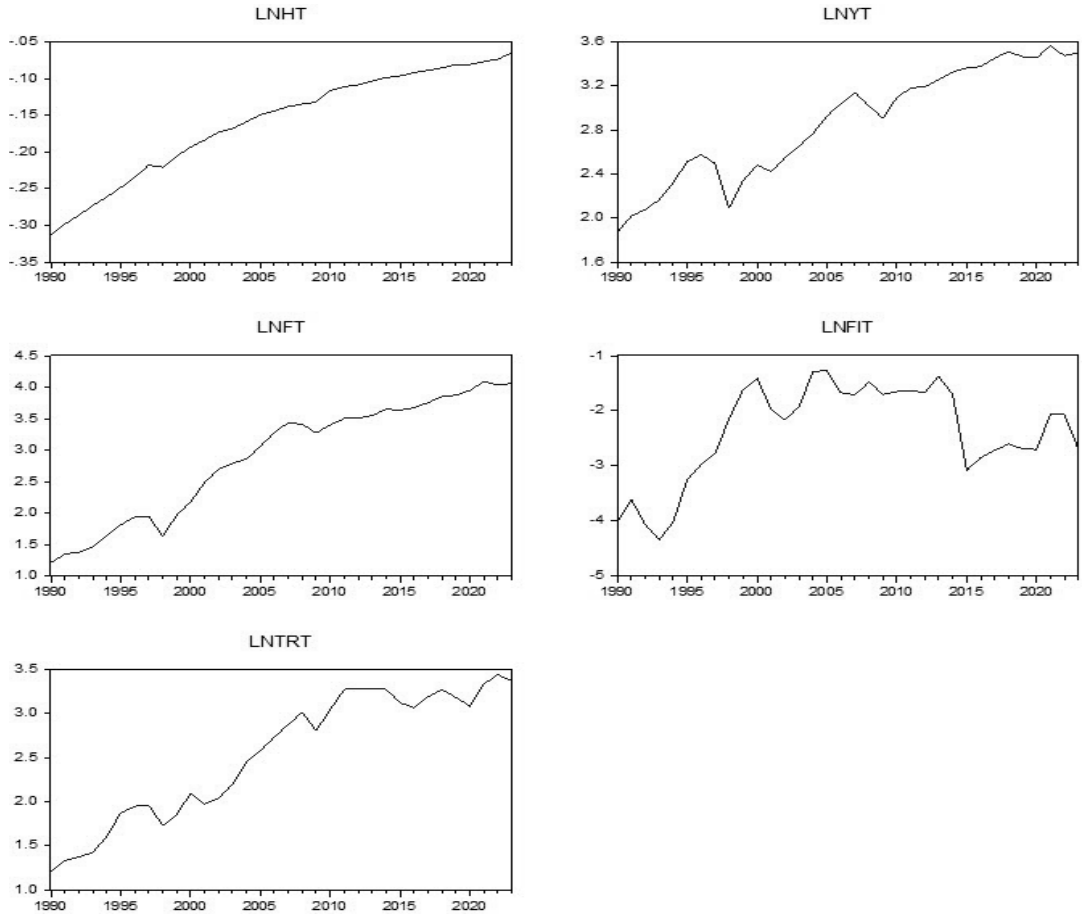


Figure 2. Korean variables.

Sources: World Development Indicators (2025). http://www.worldbank.org.
UNDP-Human Development Report (2024). http://hdr.undp.org.

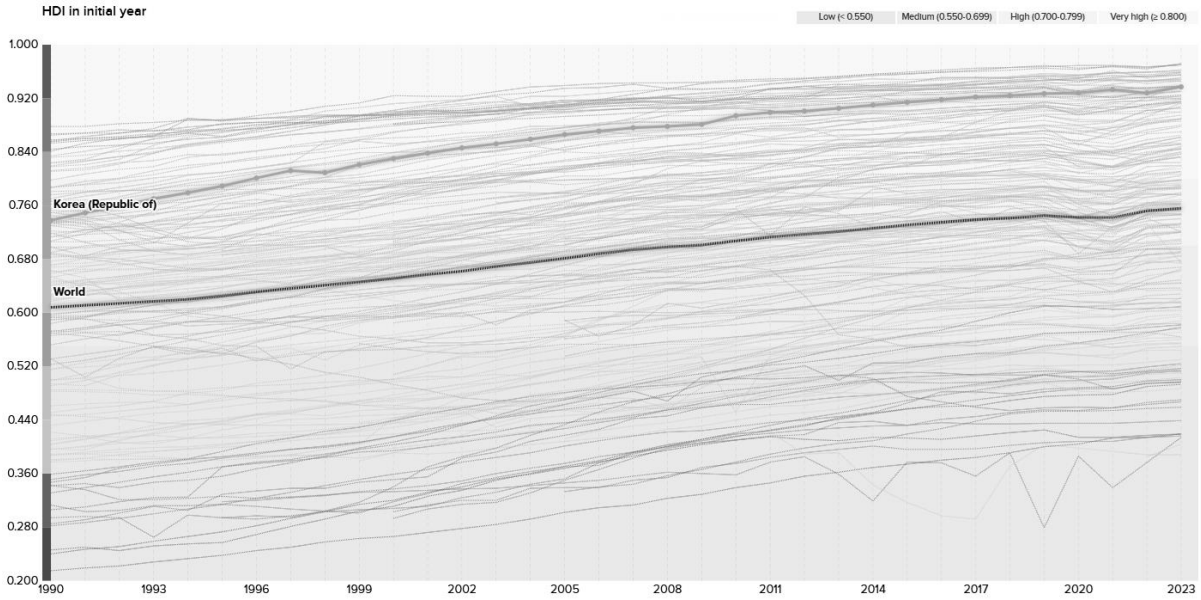


Figure 3. Korean Human Development Index 1990-2023 (captured 2026-01-23 3:13 pm).
UNDP-Human Development Report (2024). http://hdr.undp.org.
https://hdr.undp.org/data-center/human-development-index#/indicies/HDI

5.2 Unit root tests

Unit roots are nonstationary autoregressive (AR) or autoregressive moving average (ARMA) time series processes that may include an intercept or trend. Common in economics and finance, unit root tests evaluate the null hypothesis of a unit root against stationary alternatives (Herranz 2017).

The results for the Phillips-Perron (PP) test from 1990 to 2023 for the variables $\ln H_t$, $\ln Y_t$, $\ln F_t$, $\ln FI_t$, and $\ln TR_t$ are summarized in Table 5. The findings indicate that all tests consistently show that the level data for all variables are nonstationary. However, the first differences of these variables exhibit stationarity at a 1% critical level.

Table 5. Phillips-Perron unit root test

Variables	P-P		
	Level	1st difference	2nd difference

$\ln H_t$	-17.3134***	-4.18575***	-40.1236***
$\ln Y_t$	-1.71501	-6.11692***	-24.9484***
$\ln F_t$	-1.9842	-4.78967***	-18.0496***
$\ln FI_t$	-2.01349	-4.28165***	-10.5926***
$\ln TR_t$	-1.83247	-5.03607***	-16.2027***

Sources: World Development Indicators (2025). http://www.worldbank.org
UNDP-Human Development Report (2024). http://hdr.undp.org
Note: *** indicates 1% significance level. Phillips-Perron critical value is taken from MacKinnon (1991, 1996).

5.3 Johansen cointegration test

In their research, the trace statistic and the maximum eigenvalue statistic were estimated using the Johansen cointegration approach (Johansen 1988; Johansen and Juselius 1990), as presented in Table 6. The results indicate one cointegration relationship at the 0.05 significance level, allowing us to reject the null hypothesis. However, trace and maximum eigenvalue statistics can conflict, so the choice between them depends on clarity (Johansen and Juselius 1990).

Table 6. Johansen cointegration test

Unrestricted cointegration rank test (Trace)

Hypothesized No. of CE(s)	eigenvalue	Trace statistics	0.05 Critical value	Prob.**
None *	0.635579	92.86782	69.81889	0.0003
At most 1	0.573218	60.56558	47.85613	0.0021
At most 2	0.425752	33.31814	29.79707	0.0189
At most 3	0.269864	15.56794	15.49471	0.0488
At most 4	0.157999	5.503754	3.841466	0.019

Trace test indicates 5 cointegrating eqn(s) at the 0.05 level
*denotes rejection of the hypothesis at the 0.05 level
**Mackinnon-Haug-Michelis (1999) p-values

Unrestricted cointegration rank test (Maximum eigenvalue)

Hypothesized No. of CE(s)	eigenvalue	Max-eigen statistics	0.05 Critical value	Prob.**
None	0.635579	32.30224	33.87687	0.0761
At most 1	0.573218	27.24745	27.58434	0.0552
At most 2	0.425752	17.7502	21.13162	0.1395

At most 3	0.269864	10.06478	14.26460	0.2077
At most 4	0.157999	5.503154	3.841466	0.019

Sources: World Development Indicators (2025). http://www.worldbank.org UNDP-Human Development Report (2024). http://hdr.undp.org

Max-eigenvalue test indicates no cointegration at the 0.05 level

* denotes rejection of the hypothesis at the 0.05 level.

**Mackinnon-Haug-Michelis (1999) p-values.

5.4 Hindcast Evaluation

The accuracy of the Korean hindcast data, spanning from 1990 to 2023, is evaluated using several statistical measures: mean absolute percentage error (MAPE), mean absolute error (MAE), root mean squared error (RMSE), and the Theil inequality coefficient (Makridakis et al. 1998; Fair 1986; Sohn 2019). These statistics provide a quantifiable distance between the hindcast values and the actual observed values, which are presented in Table 7 and Figure 4.

Table 7. Korean hindcast evaluation 1990-2023

Variable	Obs	RMSE	MAE	MAPE	Theil
$\ln H_t$	33	0.002254	0.001678	1.226173	0.006670

Sources: World Development Indicators (2025). http://www.worldbank.org UNDP-Human Development Report (2024). http://hdr.undp.org

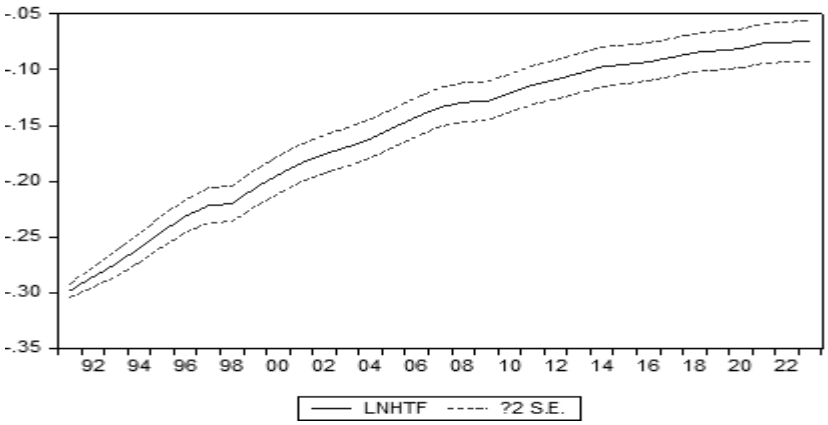


Figure 4. Korean hindcast evaluation 1990-2023.

Sources: World Development Indicators (2025). http://www.worldbank.org UNDP-Human Development Report (2024). http://hdr.undp.org

6. Empirical Results and Discussion

6.1 Long-run Causality Tests

The estimation results for Equations (5), (6), and (7) are presented in Table 8. The table indicates that the ARDL bounds testing for cointegration reveals F-statistics that meet the lower bound at the 1% significance level concerning CO_2 emissions. This suggests that a cointegration relationship exists among the variables during the period from 1990 to 2023. Therefore, financial development, GDP, FDI, and trade are cointegrated with HDI, indicating a long-run relationship in the Korean economy.

Table 8. Long-run causality tests

Estimated equation	$\ln H_t = f(\ln Y_t, \ln F_t, \ln FI_t, \ln TR_t)$		
Optimal lag structure	(1, 0, 1, 0, 0)		
F-statistic	7.815227		
Significance	Critical values		
	Lower bound I(0)	Upper bound I(1)	
1%	3.74	5.06	
5%	2.86	4.01	
10%	2.45	3.52	
Dependent variable: $\ln H_t$			
Variable	Coefficient	T-statistic	Prob.
$\ln Y_t$	0.024386	0.88567	0.3831
$\ln F_t$	0.054492	4.219285***	0.0002
$\ln FI_t$	0.007902	2.186169	0.037
$\ln TR_t$	0.00667	0.380647	0.7062
Constant	-0.38532	-14.296	0.0000
Diagnostic test			
R^2	0.977789		
Adjusted R^2	0.974725		
F-statistics	319.1657(0.000000)***		
SERIAL	17.16018(0.000)		
ARCH	3.277659(0.0799)		
WHITE	2.76223(0.0205)		
RAMSEY	2.117531(0.1567)		
CHOW	5.672781(0.0014)		

Sources: World Development Indicators (2025). http://www.worldbank.org UNDP- Human Development Report (2024). http://hdr.undp.org

Note: *** denotes 1% significant level. The numbers in parenthesis are probability values. *SERIAL* is for Lagrange multiplier (LM) serial correlation test, *ARCH* for autoregressive

conditional heteroskedasticity, *WHITE* for white heteroskedasticity, *RAMSEY* for Ramsey Reset test and *CHOW* breakpoint test.

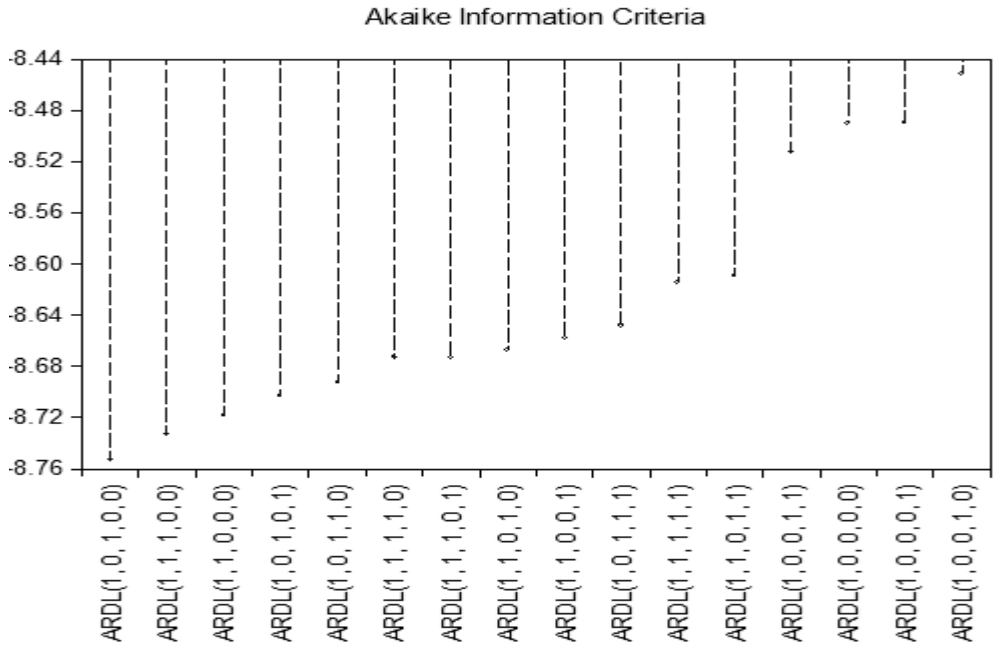


Figure 5. Akaike information criteria.
Sources: World Development Indicators (2025). http://www.worldbank.org.
UNDP-Human Development Report (2024). http://hdr.undp.org.

The Figure 5 model was selected based on the Akaike Information Criterion (AIC), resulting in an autoregressive distributed lag (1,0,1,0,0) equation with a maximum lag of 1. The computed F-statistic exceeds the upper critical bound at the 1% significance level, further reinforcing the previous results.

The empirical findings presented in Table 8 illustrate the effects of economic growth, foreign direct investment (FDI), and trade on the Human Development Index (HDI). Specifically, ceteris paribus, a 1% increase in economic growth raises HDI by 0.024386%. Additionally, other variables constant, a 1% increase in trade openness results in a 0.00667% increase in HDI. Furthermore, ceteris paribus, a 1% increase in financial development raises HDI by 0.054492%. Holding other variables constant, a 1% increase in FDI contributes to an increase in HDI by 0.007902%.

The empirical evidence indicates that a long-run causal relationship exists between GDP and financial development concerning HDI in Korea. This finding aligns with the conclusions of Ang (2008).

6.2. Short-run Causality Tests

The empirical results from the estimation of Equations (5), (8), and (9) are presented in Table 9. The findings demonstrate a positive and significant relationship between economic growth and the Human Development Index (HDI) in Korea. Holding other variables constant, a 1% increase in economic growth raises the HDI by 0.009963%. Similarly, with other factors unchanged, a 1% increase in financial development leads to a 0.015098% increase in HDI.

Table 9. Short-run causality tests

Dependent variable: $\Delta \ln H_t$			
Variable	Coefficient	T-statistic	Prob.
$\Delta \ln Y_t$	0.009963	0.766514	0.4498
$\Delta \ln F_t$	0.015098	1.428805	0.1614
$\Delta \ln FI_t$	0.002108	0.970855	0.3399
$\Delta \ln TR_t$	0.002118	0.220791	0.8269
Constant	0.005245	5.40142	0.0000
Diagnostic test			
R^2	0.40969		
Adjusted R^2	0.325359		
F-statistics	4.858167(0.004202)***		
SERIAL	4.621335(0.0192)		
ARCH	0.208415(0.6513)		
WHITE	1.212921(0.3448)		
RAMSEY	0.147843(0.7036)		
CHOW	3.380766(0.0196)		

Sources: World Development Indicators (2025). http://www.worldbank.org. UNDP-Human Development Report (2024). http://hdr.undp.org

Note: *** denotes 1% significant level. The numbers in parenthesis are probability values. *SERIAL* is for Lagrange multiplier (LM) serial correlation test, *ARCH* for autoregressive conditional heteroskedasticity, *WHITE* for white heteroskedasticity, *RAMSEY* for Ramsey Reset test and *CHOW* breakpoint test.

The relationship between Foreign Direct Investment (FDI) and Human Development Index (HDI) is both positive and statistically significant. Holding other variables constant, a 1% increase in FDI results in an increase in HDI by 0.002108%. All else being equal, a 1% increase in trade openness increases HDI by 0.002118%.

6.3 Discussion

Tables 8 and 9 indicate a unidirectional causality from GDP to broad money and from bank credit to GDP. In Korea, a bidirectional relationship exists between financial development, human capital accumulation, and GDP, suggesting a virtuous cycle of growth. Endogenous growth models explain how advanced economies sustain long-term growth, while the extended neoclassical framework highlights differences in growth rates among countries, such as South Korea's rapid expansion compared to the U.S. and Zaire. Together, these theories illuminate economic growth dynamics (Barro 1999).

The diagnostic tests, including the Lagrange Multiplier (LM) test, ARCH test, White's test, Ramsey's RESET, and Chow test, show that both short- and long-run models passed successfully. A causal relationship exists among financial development, economic growth, foreign direct investment (FDI), trade, and the human development index (HDI) in both time frames. Figures 6 and 7 present the stability test graphs, specifically the CUSUM and CUSUMSQ tests (Ploberger and Krämer 1990), which assess the constancy of the regression relationships over time. The stability of the coefficients in the regression equations was evaluated using the Chow test (1960), Brown et al. (1975), Hansen (1992), Hansen and

Johansen (1992), and Quintos (1998). The graphs remain within the critical bounds at the 5% significance level, indicating that all variables analyzed are relatively stable and consistent.

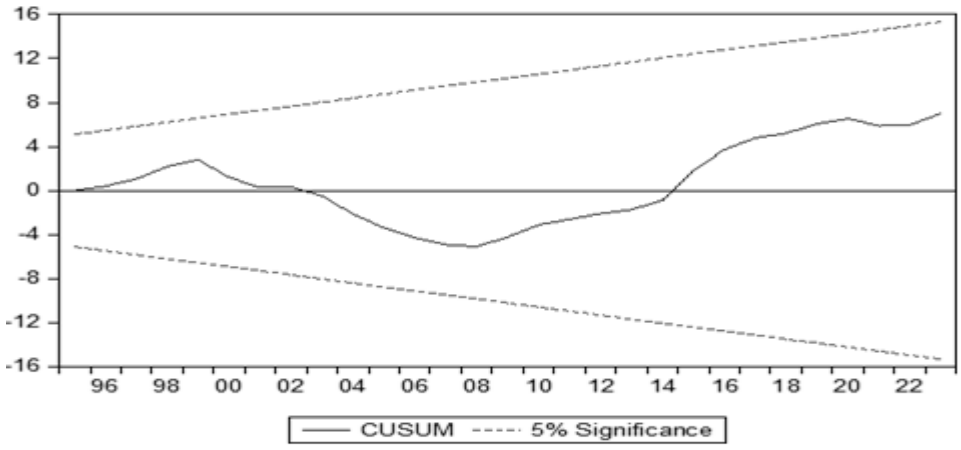


Figure 6. CUSUM of the conditional model
Sources: World Development Indicators (2025). http://www.worldbank.org.
UNDP-Human Development Report (2024). http://hdr.undp.org.
Note: The straight lines represent critical bounds at 5% significance level.

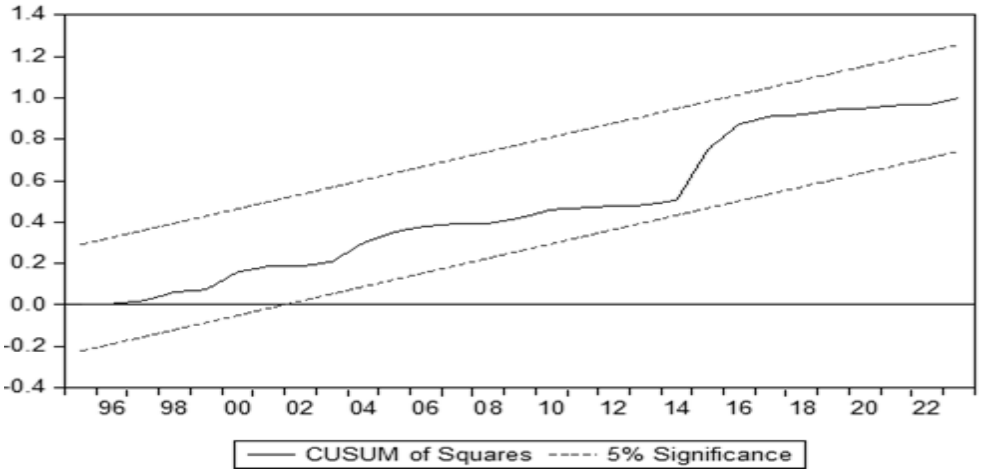


Figure 7. CUSUM of squares of the conditional model
Sources: World Development Indicators (2025). http://www.worldbank.org.
UNDP-Human Development Report (2024). http://hdr.undp.org.
Note: The straight lines represent critical bounds at 5% significance level.

7. Conclusion

This study examines the causal relationship between human capital and sustainable development in Korea from 1990 to 2023. It employs the Error Correction Model (ECM) and the Autoregressive Distributed Lag (ARDL) bounds testing approach to analyze the long- and short-term relationships among the relevant variables.

Recent research indicates that improvements in human capital exert a more significant impact when considering the quality of education and the role of human capital in the innovation process (Baily et al. 2021). Economic success fundamentally depends on human capital—defined as the knowledge, skills, competencies, and attributes that enable individuals to contribute to their own well-being, that of society, and that of their countries (OECD 2007). The Brundtland Report (WCED 1987) defines sustainable development as development that satisfies the needs of the present generation without compromising the ability of future generations to meet their own needs (Pezzey 1989; Pearce et al. 1989; Rees 1990; Lélé 1991; Stern 1997). Barro (1999, 2001) argues that human capital accumulation is a crucial aspect of the development process (Benhabib and Spiegel 1994; Hartog and Brink 2007; Mamuneas et al. 2006). Ethical universalism demands impartiality both within and between generations (Anard and Sen 2000). The moral responsibility towards future generations, embedded in the concept of sustainability, emerges as a requirement of justice (Dower 2004). This highlights that sustainability may be a necessary condition for justice (Barry 1997).

Sensitivity analysis can be used to assess how responsive a latent human capital model is to changes in parameter values and its structural framework (Breierova and Choudari 2001; Saltelli 2009). There are numerous reasons to measure investments in human capital and the resulting human capital stock. The development of human capital is central to modern theories of economic growth (Lucas 1988; Romer 1990; Barro and Sala-i-Martin 1995).

Three primary approaches are commonly adopted for measuring investments in formal education and the resulting human capital stock: the indicator approach, the cost approach, and the income approach (Le et al. 2005; Jones and Fender 2011; UNECE 2016; Abraham and Mallatt 2022).

Research consistently reveals a strong causal link between human capital and sustainable development. As a vital component of the innovation process (Howitt and Aghion 1998), human capital not only drives progress but also plays a critical role in fostering sustainable development by optimizing utility over the long term. To fully understand this dynamic, future studies should delve into similar patterns across diverse sectors and countries, providing valuable comparative insights that could inform policy and practice.

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