REBS Review of Economic & Business Studies

Volume 19, Issue 1/June 2026, pp. 11 of 32
ISSN-1843-763X
DOI: 10.47743/rebs-2026-1-0001

ECONOMIC COMPLEXITY, ECONOMIC GROWTH, AND CO_2 EMISSIONS: A GLOBAL PERSPECTIVE

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Abstract: *This study investigates the dynamic interplay among economic complexity, carbon dioxide (CO_2) emissions, and economic growth using a Cobb–Douglas production framework and panel data for 116 countries spanning 1990–2017. We estimate a system of simultaneous equations through the Generalized Method of Moments (GMM). The analysis reveals a bidirectional causal link between economic complexity and economic growth, primarily driven by high-income economies. Moreover, a reciprocal relationship exists between economic growth and CO_2 emissions. While greater economic complexity tends to raise CO_2 emissions, increased emissions in turn reduce economic complexity. The evidence also points to a U-shaped association between complexity and growth. Overall, the findings highlight a tension between advancing economic sophistication and achieving environmental sustainability. Policymakers should consider this trade-off when designing innovation and industrial strategies that aim to foster both productivity and ecological balance.*

Keywords: *Economic complexity, CO2 emissions, Economic growth, GMM*

JEL Classification: *G21, G28*

1. INTRODUCTION

Economic complexity brings significant economic benefits and is a crucial factor of long-term,, economic development (Hidalgo & Hausmann, 2009). However, the multifaceted discourses on its ecological footprints elicited an array of clashing perspectives. More complex economy, characterized by sophisticated products and diverse industries, can lead to energy-efficient production, adoption of green innovations, and sustainable business practices (Mealy & Teytelboym, 2022; Wang et al., 2023). Another strand of literature highlighted how economic complexity is often seen as the precursors to higher resource consumption and environmental degradation (Shahzad et al., 2023; Doğan et al., 2019; Neagu, 2019; Qayyum et al., 2021; Boleti et al., 2021). Even though the move towards knowledge-intensive economies offers

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significant economic benefits (Chu, 2026), further intensification of knowledge-driven innovation might result in an economy-wide rebound effect, potentially intensifying energy consumption and escalating carbon emissions (Sorell, 2009; Jevons, 1865). Therefore, a theoretical model that elucidates the complex interactions among economic complexity, economic growth, and environmental pollution significantly contributes to academic literature and provide the basis for developing sound economic policies.

There is a large body of literature that examines the relationships between the pairs among economic complexity, economic growth, and environmental emissions. This study turned this area of research into a trivariate investigation due to several reasons. First, the bivariate models are associated with omitted variable bias and likely leading to misleading causality results (Lutkepohl, 1982). Incorporating a third variable would deliver more valid results and more comprehensive analysis of these relationships. Second, the relationships among economic growth, emissions, and economic complexity are dynamic and bidirectional, with multiple feedback loops influencing how these variables interact with each other. This study aims to examine the existence of bidirectional causalities in a trivariate framework of dynamic simultaneous equations. Finally, economic activities are often viewed as producing economic benefits at the expense of environmental performance, reflecting the inherent trade-offs between economic development and environmental sustainability (Arrow et al., 1995; Kuznets, 1955). Knowledge-intensive economy plays a vital role in sustainable growth and prosperity (Wang et al., 2022; Mealy & Teytelboym, 2022). Examining the trivariate framework of economic growth, carbon emissions, and economic complexity is essential for developing a holistic understanding of how these variables interact.

The rest of the paper is organized as follows. Section 2 presents over the literature. Section 3 describes the data and the econometric methodology. Section 3 presents the results and discussion. Section 4 concludes this paper with some policy implications.

2. LITERATURE REVIEW

Economic complexity is a framework developed by Hausmann and Hidalgo (2009) that explains the wealth and economic growth of nations by investigating the complexity of their economic activities. It suggests that national wealth is not solely dictated by traditional factors such as natural resources and labor, but also by the diversity and sophistication of its productive capabilities. According to economic

complexity theory, the spectrum of products emanated by a nation disclosed greatly about its economic landscape, workforce, infrastructure, and institution. Hausmann and Hidalgo (2009, p.10575) call out to emphasize the "specificity and complementarity" of production factors such as physical and human capital, rather than only focuses on their mere accumulation. Economic complexity theory states that countries with more complex and diverse economies are better equipped to make and export "less ubiquitous products" (Hausmann and Hidalgo, p. 10571). One assertion of the economic complexity theory, which is also justified by our study is that economic complexity is a significant forecaster of sustainable economic growth and resilience since higher level of economic complexity tend to have positive association with higher income. Hausmann and Hidalgo (2009, p.10575) stated that "countries with many capabilities will be able to combine new capabilities with a wide set of existing capabilities, resulting in new products of higher complexity than those of countries with few capabilities", highlighting the essence of national range of capabilities.

The three propositions of economic complexity theory are about the Product Space framework (1), the Economic Complexity Index (2) and the effects of enhanced economic complexity (3). Our study is a contribution to economic complexity theory because it uses the Economic Complexity Index to address the third proposition that is enhancing economic complexity enables the development of new capabilities and the upgrade of existing ones.

The central method of economic complexity theory is the development of complexity metrics. Complexity metrics were discovered by using international trade date to forecast future economic growth (Hidalgo 2021). In theory, the complexity of a product is defined by the number of capabilities required to produce it. The complexity of a country's total output is the number K of capabilities its production consists of. Researchers come up with the Economic Complexity Index (ECI) which is the estimate of the number of capabilities mentioned above and is computed using international export data and is put into a framework linking countries and products that they make (Inoua, 2023). Hidalgo (2021, p.1) suggests that complexity methods enable the illustration of detailed economic structures which are useful for the introduction of appropriate industrial policy".

2.1. Economic complexity and country-level innovation

Economic complexity is a holistic measure of the sophistication of a country's productive structure, showcasing the amount of knowledge embedded in its products (Hidalgo & Hausmann, 2009). This measure is positively correlated with a country's income level, playing a vital role in achieving sustained growth and prosperity (Hidalgo

& Hausmann, 2009). The diversity of capabilities available in a country can drive a country's productivity, making economic complexity a key factor in explaining variations in economic growth across countries. Felipe et al. (2012) highlights that high-complexity nations like Japan, Germany, the U.S.A., and France are among the world's wealthiest, whereas countries with lower complexity, such as Cambodia, Papua New Guinea, and Nigeria, tend to have lower income per capita. Nations like China, India, Poland, and Brazil have shown significant economic improvement over time, attributed to the accumulation of production capabilities, i.e., economic complexity (Felipe et al., 2014).

The economic complexity index (ECI) was developed by Hidalgo and Hausmann to quantify the productive capabilities of countries and the complexity of their economics. The ECI is available in The Observatory of Economic Complexity. The ECI is based on the principle that the diversity and sophistication of a country's exported products reflect the complexity of its economy and its capacity to produce an expansive range of goods and services. Some information required to calculate ECI includes export data, product space analysis which is a network representation of the relationship between different types of products based on their co-export pattern and country's export basket. To calculate the ECI of a country, firstly the comparative advantage of each exported product is computed. After that, the comparative advanatges of all exported products are aggregated and normalized into z-scores.

The relationship between economic complexity and national innovation has been inconclusive. Nations with higher level of economic complexity possess a broader spectrum of productive knowledge, enabling them to manufacture a diverse array of goods, including complex products that few other countries can produce. There are several reasons why higher levels of economic complexity could bolster national innovation. First, the Economic Complexity Index, a novel metric assessing the complexity of an economic system, in increasingly used to approximate innovative output (Sweet & Eterovic, 2019; Vu, 2022). It reflects the institutional frameworks that underpin patent rights and protection, crucial for innovation (Sweet & Eterovic, 2019). Second, the introduction of innovative products and new technologies requires the complex recombination from a variety of knowledge sources, the integration of different competencies, and the application of numerous technological components (Barbieri et al., 2020). As knowledge forms the foundation of innovation (Fleming and Sorenson, 2001; Horbach et al., 2012), a country's ability to access a wide array of knowledge is essential for producing technologically advanced and innovative products (Hausmann et al., 2014). This aspect is closely linked to innovation, which inherently requires a rich mix of tacit and explicit knowledge within the economy (Vu, 2022).

Therefore, a country with greater economic complexity indicates a rich source of collective knowledge that can be utilized for developing economic and societal innovations (Hidalgo and Hausmann, 2009). By coordinating the efforts of various knowledge holders, complex economies can enhance the ability to assimilate new knowledge and leverage existing knowledge for innovation and thus tend to export more technologically advanced products (Balland et al., 2022).

The complexity of economic structures, while often beneficial, can impede national innovation in several ways. First, a high degree of complexity increases interdependencies among knowledge domains during innovation searches (Yayavaram & Chen, 2014), leading to a broader range of potential combinations and significant great uncertainty about their value, ultimately diminishing innovation performance. Second, highly complex interdependencies among knowledge domains mean that a change in one knowledge domain can necessitate adjustments across many other domains, raising the costs of innovation searches. The surge in opportunities due to heightened economic complexity may surpass the managerial, technological, and financial capacities of many new market entrants (Nguyen et al., 2021). The third drawback is the diminishing returns associated with relying on the same knowledge base. While countries and societies build knowledge by repeating tasks (Acemoglu & Zillibotti, 1999), economic complexity, reflecting this accumulated knowledge through indicators like research and development (R&D) expenditure or patent counts (Du & O'Connor, 2021), faces inherent limits. The benefits of leveraging the same knowledge elements wane once the maximum potential of that knowledge trajectory is reached (Dosi, 1988), particularly with complex knowledge bases. This results in diminishing returns to R&D investment across firms and industries (Jaruzelski et al., 2011; Ravichandran et al., 2017), where the costs of further development based on the same knowledge soar, and the incremental benefits of product development diminish.

The foundation for economic complexity and innovation output of a nation is the economic complexity and institutional theory. Firstly, according to economic complexity theory, nation's income tends to connect with the complexity of their productive structure (Hausmann et al., 2021). Economic complexity is measured by the capabilities and know-how embedded in the production of goods and services. The Economic Complexity Index is the summary between a country's diversification and a product's ubiquity. Economic complexity theory suggests that nation can generate and sustain long-term growth by diversifying its know-how and increasing more complex goods and services it can produce and provide. Secondly, the institutional theory gives credit to the social elements namely cognitive pillar, formative pillar and regulative pillar, as foundations for organizational structure. According to Scott (2008),

institutional theory emphasizes productivity, ethics and legitimacy. According to institutional theory, in order to survive, organizations must conform to the rules and beliefs that are ubiquitous in the environment (DiMaggio andn Powell, 1983; Meyer and Rowan, 1977; Vu, 2023; Chu & Tran, 2025) because institutional isomorphism will bring in legitimacy to the organizations. Institutional theory suggests that in a business environment where economics is built on complex and unique knowledge, organizations must upgrade and refine their capacities and knowledge to sustain themselves. Otherwise, they will become outdated and extinct. This theory explains how economic complexity have an impact on country-level innovation.

To this end, while economic complexity is generally associated with increased national innovative capacity due to the diversity and sophistication of knowledge it encapsulates, there exists a threshold beyond which the benefits of economic complexity begin to diminish. Beyond this point, the intricate interdependencies and the vast array of potential knowledge combinations introduce significant uncertainties between economic complexity and national innovation capacity, where the initial positive impact of complexity on innovation may eventually plateau or even decline as the complexity reaches excessively high levels. In light of these arguments, we propose:

Hypothesis 1: Economic complexity has an inverted U-shaped impact on national innovative capacity.

2.2. Entrepreneurship and Innovation at the country level

Despite the strong interconnection between innovation and entrepreneurship as highlighted by Bessant & Tidd (2007) and Chu et al. (2025b), scholarly work has often treated the phenomena of country-level entrepreneurship and national innovation capacity as two distinct phenomena (Mrożewski & Kratzer, 2017). The interplay between these two constructs is intricate, with limited empirical research shedding light on the dynamics of their relationship. This complexity arises from the dual nature of entrepreneurship: under certain conditions, it acts as a catalyst for a a country's capability to generate commercially viable innovations, while in other scenarios, it may detract from the nation's overall innovative prowess. This discussion briefly examines the dual outcomes of this relationship.

Entrepreneurship can bolster a nation's innovative capacity through two primary mechanisms, by fostering the creation of innovation (Schumpeter, 1934) and by stimulating competition that encourages the emergence of innovative new ventures (Kritikos 2016; Matusik 2016).

The classical work of Schumpeter (1911), conceptualizing "entrepreneur as innovator" and envisioning entrepreneurship as a force that initiates a "creative

destruction" process, contributed to understanding the entrepreneur's role as a catalyst for economic transformation (Aghion & Howitt, 1992). This process rejuvenates the market by replacing outdated practices with new innovations, thereby leading to a dynamic market realignment towards equilibrium. This cycle of disruption explains the observed correlation between a high rate of entrepreneurial activity and increased innovation within the economy, as the disturbances introduced by innovative entrepreneurs stimulate further entries into the market and, subsequently, more innovations.

Central to entrepreneurial process are entrepreneurs who, according to Shane & Venkataraman (2000), are committed to turning new ideas into profitable ventures through determined and persistent efforts. Barron (2007) highlights the crucial role of entrepreneurs in translating potential ideas into market-relevant innovations, indicating that without their initiatives, promising concepts may remain unrealized. The concept of "innovating entrepreneurs" refers to individuals who deploy their distinct capabilities for innovation, engaging novel ideas, experimentation, and creativity that could result in breakthrough products, services, or technological processes (Lumpkin & Dess, 1996).

Additionally, entrepreneurship serves as a bridge facilitating the dissemination of knowledge from established companies to new market players, thus enabling the commercial exploitation of ideas that original innovators did not pursue (Acs et al., 2009). This knowledge-spillover effect allows previously untapped valuable knowledge to find its way to market through new ventures, thereby indirectly fostering economic growth through technological investments (Audretsch & Keilbach, 2008).

Entrepreneurship, while often a driver of innovation, can adversely impact a nation's innovative capacity in certain scenarios. This negative effect is primarily seen in the activities of entrepreneurs who engage in non-productive or detrimental behaviors, such as rent-seeking, corruption, tax evasion, and organised crimes, which can erode the country's ability and enthusiasm for generating beneficial innovations (Brück et al. 2013; Baumol, 1996). Several factors explain why an excessively level of entrepreneurial efforts might result in a reduced rate of innovation nationally.

First, the vast number of start-ups that emerge each year, with many failing to generate meaningful innovations or create jobs that contribute to economic growth, points to a misallocation of resources (Shane, 2008). This overabundance of entrepreneurial activity tend to be associated with rent-seeking behaviors, where the influx of start-ups does not translate into innovative contributions or significant wealth generation (Canh et al., 2021).

Second, the mismatch between the number of start-ups and the available entrepreneurial opportunities often results in a landscape dominated by necessity entrepreneurs. Such entrepreneurs, typically propelled into entrepreneurship by lack of alternatives, like unemployment, are less likely to innovate due to constraints in talent and resources (Mrożewski & Kratzer, 2016; Thurik et al., 2008). Necessity-driven ventures, often characterized by their limited potential for growth and innovation, contribute minimally to the economy's overall innovative dynamism (Wong et al. 2005; Shane 2009). The prevalence of necessity entrepreneurship, which tends to eschew innovation-focused strategies, can thus lead to a lower level of national innovation (Anokhin & Wincent 2012), highlighting the complexity of entrepreneurship's impact on innovation at the country level.

Hypothesis 2: Entrepreneurship has an inverted U-shaped impact on national innovative capacity.

2.3. The interactive effect between economic complexity and entrepreneurial activity

Discussing entrepreneurship involves exploring the distinctive personalities and capabilities of entrepreneurs who innovate by introducing new ideas, products, services, markets, or technologies, thereby creating value (Gartner, 1990). According to the "discovery view", opportunities are seen as existing objectively and independently, waiting to be identified and exploited by enterprising individuals (Eckhardt & Shane, 2003; Shane, 2003). Entrepreneurs dedicate considerable effort to ideation, researching, and spotting fresh opportunities (Kaish & Gilad, 1991). At the national level, entrepreneurship characterized by the pursuit of opportunities is closely linked with technological advancement and innovation (Mrożewski & Kratzer, 2017). Essentially, while economic complexity captures the collective knowledge within an economy, national-level entrepreneurship embodies the concerted pursuit of innovation and information. In this section, we posit that economic complexity and entrepreneurship not only contribute uniquely to national innovation capacity but also interact in mutually beneficial ways. The synergy between these two constructs is underscored by a nation's ability to absorb and apply new knowledge and its drive towards uniqueness, fostering a positive interplay that enhances innovation.

Within an organization, absorptive capacity is defined as "the ability of a firm to recognize the value of new, external information, assimilate it and apply it to commercial ends" (Cohen & Levinthal 1990, p.128). The effectiveness with which a firm leverages its absorptive capacity is significantly influenced by its historical decisions and capabilities. Cohen and & Levinthal (1990, p.128) articulate that the "lack

of investment in an area of expertise early on may foreclose the future development of a technical capability in that area." Simply put, firms are unable to apply innovations if they do not command required capabilities and prior knowledge.

This view mirrors the rationale behind the economic complexity index on a national scale, as proposed by Sweet & Eterovic (2019). The idea that just as firms can only acquire and implement knowledge if they possess the necessary capabilities, advantages, and components from their networks – akin to a child being "able to produce a Lego model if the child's bucket contains of all the necessary Lego pieces" (Hidalgo & Hausmann, 2009, p. 1057). Extending this analogy to the national level, countries can only produce goods for which they possess all the essential capabilities. This perspective emphasizes the parallel between how organizations and nations alike build upon existing knowledge and capabilities to foster innovation and productivity. We call this the first mechanism through which nations develop their innovation capacity through the interaction of economic complexity and entrepreneurial activities.

A decade ago, Alfred Marshall posited that "Knowledge is the engine of growth", a statement that has been extensively supported by research on absorptive capacity. This body of literature underscores knowledge as a pivotal element of economic growth, highlighting its role in creating a skilled national workforce adept at assimilating and applying new technologies and knowledge developed in other countries (Foster-McGregor et al., 2017; Huebler et al., 2016; Khordagui & Saleh, 2016; Silajdzic & Mehic, 2015) as well as from foreign companies (Ying-Chun et al., 2009). It also facilitates the adaptation of techniques across diffeent sectors (M. Kim, 2015). Economic complexity, in this context, serves as an indicator of the breadth of knowledge embedded within the economic activities of a country or region (Hidalgo et al., 2007). It signifies how nations leverage their build-up internal capabilities to discern, assimilate, and capitalize on novel competencies (Hidalgo & Hausmann, 2009), thus embodying Marshall's vision of knowledge as cornerstone of growth.

New knowledge is a collection of fragments of possibly useful knowledge (Winter, 1984) and the identification and development of novel concepts demand that firms effectively tackle complementary challenges (Katila & Ahuja, 2002) or leverage pre-existing national assets like human capital (Nelson & Phelps 1966) and R&D investments (Cohen & Levinthal, 1989). Thus, the ability of a nation to innovate and produce new products hinges on the synergistic integration of its existing knowledge base with newly acquired information. Nations endowed with a rich repertoire of existing knowledge and capabilities are better equipped to integrate new insights with a broad spectrum of pre-existing knowledge, leading to the creation of new products with greater complexity and innovation compared to those from less endowed

countries. This synergy between existing and new knowledge not only facilitates the absorption of fresh insights but also propels further innovation, indicating a strong link between a nation's economic complexity, its entrepreneurial ecosystem, and its capacity for product innovation.

The interaction between economic complexity and entrepreneurship can significantly bolster the uniqueness of a country's innovations. While launching start-ups entails notable expenses, including the high costs associated with securing debt and equity financing for new ventures (Shane, 2008), the challenge is compounded by the relatively low success rate of these entrepreneurial ventures. The majority of start-ups struggle to create substantial employment, generate significant wealth, or innovate (Shane, 2009), with the risk that their ideas may already be in use elsewhere. Nevertheless, when a country combines its accumulated, specialized knowledge – its economic complexity – with fresh entrepreneurial initiatives, it is poised to develop distinctive and viable innovations. These novel combinations not only stand out by leveraging unique insights and capabilities but also have the potential to be commercialized, thus contributing to the country's economic advancement. This is the second mechanism through which innovation capacity is enhanced by the interaction between economic complexity and entrepreneurship.

This effect can be explained by considering the interaction between economic complexity and entrepreneurship as resources that enable national innovation. Penrose (1959) emphasized the role of resources in enabling or constraining organizational growth (Penrose, 1959). Over the years, researchers have expanded Penrose's definition of resources to more than just material objects, but also "strategic resources" (Amit and Schoemaker, 1993). According to Barney (1991), strategic resources are valuable, rare and difficult to imitate, creating unique competitive advantages for organizations. Penrose' definition of resources and its logics can be useful to investigate the competitive advantages brought about by high level of economic complexity at country-level. Economic complexity depicts a country's capability to produce a wide array of goods and services, representing the diversity and sophistication of country's productive capabilities (Hidalgo & Hausmann, 2009). Within the resource-base view framework, a country's level of economic complexity is its strategic resource that makes up its competitive advantage. In addition, entrepreneurial activities entail the act of identification, creation, and exploitation of opportunity for innovation and value creation (Ireland, Hitt, Camp and Sexton, 2001). From a resource-based view perspective, entrepreneurial activities are regarded as dynamic capabilities that allow countries to utilize their resources, including its economic complexity to foster innovation and economic growth. Entrepreneurial activities enable citizens to seek for

new opportunities, leverage the national resources, explore new market and develop new knowledge and technology, thus enhancing national innovation capacity (Shane and Venkataraman, 2000; Chu et al., 2025a). The interaction between economic complexity and entrepreneurial activities is synergistic. Economic complexity denotes the level of knowledge embedded within a nation's productive structure (Lapatinas, 2019). Thus, high level of economic complexity creates a fertile environment for entrepreneurs to discover opportunities and exploit them. On the other hand, entrepreneurship encourage the exploration and exploitation of opportunities and resources available in a complex economy (Shane & Venkataraman, 2000). This interaction has a significant impact on a nation's innovation capacity. Andre van Stel, Carree and Thurik (2005) suggests that nations with higher level of human capital benefits more from entrepreneurship than less developed nations. Economic complexity supplies knowledge, infrastructure, and investment for innovation, whereas entrepreneurship drives the utilization of these embedded resources into new products, services, process and business models.

Considering the interaction between economic complexity and entrepreneurship as the development of entrepreneurial opportunity also provides a lens to understand how the interaction between economic complexity and entrepreneurial activities affects national capacity. Theory of entrepreneurial opportunity developed by Shane and Venkataraman (2000) lays the foundation for many entrepreneurship studies by proposing a conceptual framework that highlights the role of entrepreneurs in recognizing, evaluating and exploiting opportunities. Firstly, nations with high level of economic complexity offers a rich ecosystem for entrepreneurs to identify, evaluate and exploit opportunities (Hidalgo and Hausmann, 2009). As entrepreneurs face resources constraints regarding finance, human and social capital, they face difficulty in exploiting business opportunities efficiently (Shane and Venkataraman, 2000). The level of economic complexity can provide either favorable or disadvantage resources for entrepreneurial activities. According to Hausmann and Hidalgo (2009, p.10575), "countries with many capabilities will be able to combine new capabilities with a wide set of existing capabilities, resulting in new products of higher complexity than those of countries with few capabilities". Therefore, we can state that the interaction between economic complexity and entrepreneurial activities facilitates the discovery and exploitation of opportunities. In a complex economics, entrepreneurs can find opportunities in new market, technology, and institutional conditions. Hausmann et al. (2014) believe that one micro-entrepreneur alone needs to rely on others' know-how and capital, together with her own knowledge, to make modern products. On the other hand, a complex economics needs entrepreneurs who are "alert to the possibilities that

have gone hitherto unnoticed" and "are the dramatis personae of economic evolution" (Searless 2017, p. 150). In other words, without entrepreneurs, innovations would not exist, and the economy would become dead-end. In his book, Hidalgo (2015) argue that economic growth is driven by knowledge accumulation and the ability of entrepreneurs to channel this knowledge into value creation process. Secondly, once they have recognized the dynamic nature of opportunities, entrepreneurs leverage resources, capabilities and opportunities embedded in the economically complex market to generate new solutions that address the challenges and demands within the market (Alvarez and Barney, 2007). Ultimately, the core concept of the theory of entrepreneurial opportunity is value creation process which is carried out by entrepreneurs (Ardichvili et al., 2003). They create values by introducing new products or services, improving existing process to increase efficiency, and developing new organizational innovation. The interaction between economic complexity and entrepreneurship leads to the creation of value for stakeholders and society as a whole. We propose:

Hypothesis 3: The interaction of economic complexity and country-level entrepreneurship is positively related to national innovative capacity.

3. METHODOLOGY

3.1. Research Objective

The objective of this study is to examine how economic complexity, economic growth, and CO_2 emissions interact across countries over time. Annual data from 1990 to 2017 for 116 countries are used. Given the potential for reciprocal causation among the variables, all three are treated as endogenous in a system of simultaneous equations. Previous studies often assume a one-way relationship – for example, from economic growth to CO_2 emissions – but such simplifications overlook important feedback mechanisms. Economic complexity not only drives growth but is also affected by environmental outcomes. Hence, this study analyzes their mutual interdependencies within a coherent econometric framework.

To capture the linkages among economic complexity, CO_2 emissions, and growth, we employ a Cobb–Douglas production function, extended to include CO_2 emissions and economic complexity alongside capital and labor as production factors. This approach follows prior empirical research that integrates environmental and technological variables into growth models (Omri, 2013; Shahbaz et al., 2012; Sharma, 2010; Ang, 2008).

The production function can be written in its general form as follows:

$$GDP_{it} = A \times E^{\alpha it} \times C^{\alpha it} \times CS^{\alpha it} \times L^{\alpha it} \times e^{uit} \quad (1)$$

where:

GDP_{it} = real GDP per capita,

A = constant term,

$E^{\alpha it}$ = economic complexity index (ECI)

$C^{\alpha it}$ = CO_2 emissions per capita

$CS^{\alpha it}$ = capital stock,

$L^{\alpha it}$ = labor force, and

e^{uit} = error term.

Taking natural logarithms yields the log-linear form:

$$\ln(GDP_{it}) = \alpha_0 + \alpha_{1i} \ln(E_{it}) + \alpha_{2i} \ln(C_{it}) + \alpha_{3i} \ln(CS_{it}) + \alpha_{4i} \ln(L_{it}) + \pi_{it} \quad (2)$$

Log-linearization allows the parameters to be interpreted as elasticities and improves estimation efficiency. A simple linear specification does not yield consistent results. The subscript *i = 1, …, N* refers to countries, while *t = 1, …, T* represents time periods. The dependent variable *GDP* denotes real GDP per capita, and *E*, *C*, *CS*, and *L* represent economic complexity, per capita CO_2 emissions, real capital stock, and labor force, respectively. The error term *e* is assumed to be identically, independently, and normally distributed. The coefficients α_1, α_2, α_3, and α_4 represent the respective elasticities of output with respect to each input, including economic complexity, CO_2 emissions, capital stock, and labor force.

The interrelationships among these three variables are empirically examined through the following system of simultaneous equations:

$$\ln (GDP_{it}) = \alpha_0 + \alpha_{1i} \ln (ECI_{it}) + \alpha_{2i} \ln (CO_{2\,it}) + \alpha_{3i} \ln (L_{it}) + \alpha_{4i} \ln (CS_{it}) + \pi_{it} \quad (3)$$

$$\ln (ECI_{it}) = \delta_0 + \delta_{1i} \ln (GDP_{it}) + \delta_{2i} \ln (CO_{2\,it}) + \delta_{3i} \ln (L_{it}) + \delta_{4i} \ln (CS_{it}) + \delta_{5i} \ln (FD_{it}) + \delta_{6i} \ln (POP_{it}) + \pi_{it} \quad (4)$$

$$\ln (CO_{2\,it}) = \omega_0 + \omega_{1i} \ln (GDP_{it}) + \omega_{2i} \ln (CO_{2\,it}) + \omega_{3i} \ln (URB_{it}) + \omega_{4i} \ln (TOP_{it}) + \pi_{it} \quad (5)$$

Equation (3) analyzes how economic complexity, CO_2 emissions, and other factors influence economic growth. An increase in economic complexity enhances GDP per capita, indicating a positive association between the level of complexity and income (Hidalgo & Hausmann, 2009). The degree of complexity in an economy determines the types of products a country can develop in the future, as new product creation depends largely on the existing productive capabilities. Thus, a broader set of capabilities predicts higher income levels. Furthermore, Apergis & Payne (2009) and Saboori et al. (2012) suggest that CO_2 emissions also affect GDP per capita, and thus

environmental degradation can causally influence economic growth, with persistent declines in environmental quality potentially imposing negative externalities on the economy. Following De Mello (1997), we incorporate domestic capital stock (CS) and labor force (L) as traditional determinants of growth. Equations (4) and (5) specify the determinants of economic complexity and CO_2 emissions, respectively.

Equation (4) investigates the factors influencing economic complexity (ECI). Economies with higher levels of income, proxied by GDP per capita, tend to exhibit greater complexity (Rafique et al., 2021; Ikram et al., 2021). Since CO_2 emissions reflect a country's industrialization and development level, increased emissions may also affect economic complexity (You et al., 2022). Capital and labor are included as key drivers of complexity (Zhu & Li, 2008; Lee & Vu, 2020; Mukhametov, 2022). Financial development (FD), measured by total credit as a share of GDP, is expected to positively influence economic complexity (Nguyen & Su, 2021). POP represents total population, which is shown to have significant effect on carbon emissions (Islam et al., 2013).

Equation (5) focuses on the determinants of per capita CO_2 emissions. Economic complexity is generally associated with higher emissions, as most countries remain on the upward segment of the Environmental Kuznets Curve (Khezri et al., 2022; Taghvaee et al., 2022). Similarly, income growth tends to raise emissions, implying a positive relationship between GDP per capita and CO_2 levels. Urbanization (URB), measured as the urban population percentage, is an important factor affecting CO_2 emissions (Hossain, 2011). Trade openness (TOP), expressed as the sum of exports and imports relative to GDP, also plays a significant role. Andersson et al. (2009) emphasized the influence of international trade on emissions, particularly in the transport sector, showing that in China, emissions from exports exceed those from imports, underscoring the role of trade in driving carbon emissions.

3.2. The estimation method

To examine the dynamic interrelationships among carbon dioxide (CO_2) emissions, economic complexity, and economic growth, this study employs the Generalized Method of Moments (GMM) using annual data from 116 countries over the period 1990–2017. Compared with the ordinary least squares (OLS) approach, GMM offers several methodological advantages for panel data analysis. It enables the combination of cross-sectional and time-series observations, allowing for the investigation of the environment–energy–growth nexus across countries and over time. Moreover, GMM effectively controls for country-specific effects and potential endogeneity arising from explanatory variables. The GMM estimator relies on a set of instrumental variables to correct for endogeneity bias, providing consistent and efficient

estimates even when heteroskedasticity is present. Because of these properties, it is among the most widely used estimation techniques for models involving panel data and multi-directional linkages. In addition, most diagnostic tests in this analysis are performed within the GMM framework. To verify the validity of the instruments, the Hansen test of overidentifying restrictions was conducted. The results failed to reject the null hypothesis, confirming that the instruments employed are valid. The Durbin–Wu–Hausman test was also applied to assess endogeneity; its rejection of the null hypothesis indicates that OLS estimates are biased and inconsistent, thereby justifying the use of GMM as a more appropriate estimation strategy. The potential endogeneity issue that may exist should be properly addressed by the structure of our panel estimation procedure. The country noise effects can also be controlled with appropriate application of the GMM procedures.

4. RESULTS AND DISCUSSIONS

The system of simultaneous equations was estimated using two-stage least squares (2SLS), three-stage least squares (3SLS), and the generalized method of moments (GMM). However, for brevity, we present only the GMM results. Although the magnitude and sign of the coefficients are broadly consistent across the three estimation techniques, the GMM estimates prove to be statistically more reliable.

In examining the tri-directional relationships between CO_2 emissions, economic complexity, and economic growth, we employ FD, POP, URB, TOP, CS, and L as instrumental variables. To assess potential endogeneity, we implement the Durbin–Wu–Hausman (DWH) test. The null hypothesis of this test states that OLS would produce consistent parameter estimates – meaning that any endogeneity in the regressors would not bias the OLS results. Rejecting the null implies that endogeneity is indeed problematic and that instrumental-variable estimators are required.

We also apply the Pagan–Hall test to detect heteroskedasticity. The rejection of the null hypothesis of homoscedasticity confirms the presence of heteroskedasticity, thereby supporting the use of the GMM estimator as both consistent and efficient. Instrument validity is further examined using the Hansen test of overidentifying restrictions, which does not reject its null hypothesis, indicating that the chosen instruments are appropriate.

Additionally, we conduct augmented Dickey–Fuller (ADF, 1979) and Phillips–Perron (PP, 1988) unit-root tests on all variables. The results show that each series is stationary in levels. Based on these diagnostic checks, the coefficient estimates for Equations (3), (4), and (5) are reported in Tables 3, 4, and 5.

The empirical results about Equation 3 are presented in Table 3, which shows that the positive impact of economic complexity on economic growth is primarily driven by groups of high-income countries. The coefficients for ECI in high-income countries and the whole sample are 0.15 and 0.11, respectively, and the results are significant at 1%. In contrast, increasing economic complexity even decreased the level of economic growth in low-income countries (-0.38 and statistically significant at 1%). The results are intriguing and may suggest that economic complexity might have a U-shaped relationship with the level of economic growth. With poor infrastructure and underdeveloped institutional system, increasing economic complexity would bring more detriments than benefits to low-income countries. With respect to the pollution indicator, our results show that CO_2 emissions exert a significant adverse effect on GDP per capita across all sampled countries. In the panel estimates, however, the CO_2 coefficient is 0.79 and statistically significant at the 1% level, suggesting that a 1% rise in emissions is associated with a 0.79% increase in economic growth. This finding aligns with the evidence reported by Jayanthakumaran et al. (2012).

The coefficient for capital is positive and significant for middle-income countries at 0.02 and 5% level of significance but negative and significant at 5% for high-income countries. The coefficient for labor is negative and significant at 5% for high-income countries only. These results may suggest that capital and labor are no longer important determinants of economic growth.

Table 1: Results of Panel GMM estimation for Equation 3

	Dependent variable: Real GDP per capita				
	Intercept	ECI	CO2	CS	L
Low-income countries	7.48***	-0.38***	0.51***	-0.01	0.06
Middle-income countries	8.22***	-0.07	0.41***	0.02**	-0.02
High-income countries	10.43***	0.15***	1.16***	-0.06***	-0.29***
Panel	8.91***	0.11**	0.79***	-0.01	-0.05
Hansen test (p-value)	0.18				
Durbin-Wu-Hausmann	0.05				
Pagan-Hall test	0.02				

Notes: All variables are expressed in natural logarithms.
* denotes significance at the 1% level;
** at the 5% level; and *** at the 10% level.

The empirical results about Equation (4) are presented in Table 4. It appears that GDP per capita has a significant positive impact on economic complexity on high-income and middle-income countries. However, the coefficient of GDP per capita is positive but not statistically significant in low-income countries. This indicates the existence of a bidirectional relationship between economic growth and economic complexity in high-

income countries. For example, the coefficient is 14.36 in the panel sample, indicating that economic complexity will increase by 14% when there is a 1% increase in real GDP per capita. Meanwhile, except for middle-income countries, the coefficients for CO2 are negative and statistically significant at least at 10%. This finding indicates that an increase in CO2 emission will lead to a decrease in economic complexity.

Table 2: Results of Panel GMM estimation for Equation 4

	Dependent variable: Economic complexity (ECI)						
	Intercept	GDP capita	CO2	CS	L	FD	POP
Low-income countries	-2.76	0.165	-0.61*	0.02	-1.01**	0.57**	0.13
Middle-income countries	-14.64***	1.61***	0.29**	-0.39***	0.18	0.20***	0.45***
High-income countries	-69.83***	7.14***	-6.05***	-0.65*	1.49***	0.08	1.14**
Panel	-104.12*	14.36*	-7.11***	-3.80	-0.99	0.53	4.21
Hansen test (p-value)	0.11						
Durbin-Wu-Hausmann	0.02						
Pagan-Hall test	0.01						

Notes: All variables are expressed in natural logarithms.
* denotes significance at the 1% level;
** at the 5% level; and *** at the 10% level.

Table 5 reports the empirical estimates for Equation (5). The findings show that GDP per capita has a statistically significant positive effect on CO_2 emissions per capita across all country groups, suggesting that higher income levels are accompanied by reductions in per-capita emissions. This relationship, however, appears weaker in high-income economies. Trade openness, urbanization, and GDP per capita all display positive and significant coefficients, indicating that economic expansion is generally associated with greater environmental degradation. These results are in line with previous evidence, including Halicioglu (2009) for Turkey, Fodha and Zaghdoud (2010) for Tunisia, Wang et al. (2011) for China, and Arouri et al. (2012) for the MENA region. With respect to economic complexity, the analysis shows that greater complexity tends to raise CO_2 emissions in the full sample, with the effect being particularly pronounced in low- and middle-income countries. This suggests that increases in economic complexity are associated with higher levels of carbon emissions in these economies. In the panel estimates, economic complexity also exerts a significant positive influence on CO_2 emissions per capita, with a coefficient of 0.11, implying that a 1% increase in economic complexity is associated with a 0.11% rise in per-capita emissions.

Table 3: Results of Panel GMM estimation for Equation 5

	Dependent variable: CO2 emissions				
	Intercept	GDP capita	ECI	TOP	Urban
Low-income countries	-15.11***	1.90***	0.84***	0.04	0.16*
Middle-income countries	17.01***	1.86***	0.22***	0.13***	0.21***
High-income countries	-6.43***	0.82***	0.02	-0.07***	0.07*
Panel	-10.11***	1.12***	0.11*	0.22	0.17***
Hansen test (p-value)	0.14				
Durbin-Wu-Hausmann	0.01				
Pagan-Hall test	0.03				

Notes: All variables are expressed in natural logarithms.
* denotes significance at the 1% level;
** at the 5% level; and *** at the 10% level.

5. CONCLUSIONS

This study examined the dynamic interrelationships among economic complexity, CO_2 emissions, and economic growth for 116 countries between 1990 and 2017 using a Cobb-Douglas production framework and simultaneous equation models estimated with the GMM approach. The results provide several key insights. First, we find evidence of a bidirectional relationship between economic complexity and economic growth, but this effect is mainly driven by high-income economies, highlighting the heterogeneous role of economic complexity across different levels of development. Second, we confirm the existence of a two-way causal link between economic growth and CO_2 emissions, reinforcing the notion that growth and environmental degradation remain tightly coupled. Third, while economic complexity appears to increase CO_2 emissions, we also observe that rising emissions have a detrimental effect on economic complexity, pointing to a potentially adverse feedback loop. Finally, the results suggest a U-shaped relationship between economic complexity and growth, meaning that countries may initially face slower growth as they become more complex, but beyond a certain threshold, complexity accelerates growth.

These findings carry important implications for policymakers and researchers concerned with the pursuit of sustainable development. The positive feedback between economic complexity and growth – at least for advanced economies – underscores the importance of upgrading a country's productive knowledge base. However, the simultaneous rise in CO_2 emissions suggests that such structural transformation may initially come at an environmental cost. Policymakers should therefore design innovation policies that both foster complexity and incentivize greener production methods. This may include supporting the diffusion of clean technologies, encouraging eco-innovation, and integrating environmental considerations into industrial upgrading

strategies. The finding that higher CO_2 emissions eventually dampen economic complexity raises concerns that unchecked environmental degradation could hinder a country's ability to diversify into more sophisticated sectors in the long run.

Despite its contributions, this study is not without limitations. First, while the use of panel GMM addresses endogeneity concerns, potential measurement errors in economic complexity and CO_2 data may still bias estimates. Second, the sample covers a wide range of countries, but heterogeneity in institutions, technology adoption, and energy structures might affect the estimated relationships. Third, the Cobb-Douglas production specification may oversimplify the complex mechanisms linking growth, emissions, and productive capabilities, leaving out potentially relevant non-linearities or interaction effects.

Future studies could address these limitations by employing alternative measures of productive capabilities (e.g., relatedness density or knowledge space indices), exploring heterogeneity across regions or income groups more explicitly, and testing for threshold effects in greater detail. Further work could also integrate renewable energy use, institutional quality, and environmental regulation as mediating variables to better understand how countries can simultaneously increase economic complexity and reduce emissions. Moreover, case studies of individual countries undergoing structural transformation could complement these macro-level findings and provide deeper insights into the mechanisms through which complexity influences sustainability outcomes.

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DECLARATIONS

All authors declare that they have no conflicts of interest.