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A Fuzzy Analytical Framework for Examining the Effects of Demographic Variables, Human Development, and Employment on Sustainability

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ABSTRACT

This study examines sustainability in BRICS countries (Brazil, China, Egypt, India, Iran, Russia, and South Africa) by analyzing the interaction of key capitals—natural, human, social, technological, and cultural—and the growing importance of human consciousness in shaping sustainability outcomes over the period from 1993 to 2024. Using a fuzzy logic methodology, the study explores the relationship between natural resource rents (% of GDP) and variables such as population, education, employment, health, and energy intensity. The results show that human capital, especially education and social awareness, is the most influential driver of sustainability. For instance, education in China (6.85) and Energy intensity level in Egypt (5.42) demonstrate strong impacts, while health expenditure in Iran (4.81) also plays a key role. These findings indicate that enhancing education, health, and cultural awareness strengthens mental adaptability, innovation, and collective decision-making. Fuzzy logic effectively manages uncertainty and complexity in policymaking, confirming that advancing human consciousness through education and health investment is vital for sustainable development. Ultimately, human choice, guided by awareness and values, determines the sustainability trajectory of BRICS nations.

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1. Introduction

Sustainable development has emerged as a central priority in international academic and policy debates, encompassing interconnected economic, ecological, political, technological, and social dimensions. Traditional approaches that isolate these domains—such as focusing solely on technological innovation or public policy—often fail to address the complexity and interdependence of modern sustainability challenges (Askari and Parsa, 2024; Montiel-Hernández et al., 2024; Xiaoyang et al., 2022). As the 21st century progresses, the rapid advancement of technology, ongoing demographic shifts, and increasing global interconnectedness highlight the necessity for integrated frameworks that recognize the complex interactions among human, social, natural, and technological systems (Alkofahi et al., 2024; Kassier, 2024; Aguilera et al., 2021; Steffen et al., 2018). Within the context of the Anthropocene Epoch, in which human activities have emerged as the primary drivers of planetary processes, gaining insight into the role of human agency and consciousness has become increasingly essential. (Crutzen, 2016). The BRICS nations—Brazil, Russia, India, China, South Africa, along with Egypt and Iran in this study—play a central role in this transformation. These countries must balance two goals: maintaining economic growth and moving toward development that is more inclusive, knowledge-driven, and environmentally sustainable. Despite their progress, many BRICS nations still face challenges in education, health, and governance, which affect their ability to achieve long-term sustainable results (Kumar et al, 2025; Ganda, 2022). Recent research highlights that human capital—including education, skills, health, creativity, and collective awareness—plays a decisive role in shaping sustainability pathways (Becker, 2002). However, much of the existing literature treats human capital as one among several drivers of development, rather than as the primary determinant of long-term sustainability. Moreover, the inherent complexity and uncertainty of social–ecological systems call for methodological approaches that can capture nonlinear interactions as well as the qualitative dimensions of human behavior. (Jahanger et al, 2022; Kim & Go, 2020). This study addresses these gaps by examining sustainability in BRICS countries through the interaction of key capitals—natural, human, social, technological, and cultural—and the evolving role of human consciousness in shaping sustainability outcomes. Using a fuzzy logic methodology, the research investigates how variables such as population size, R&D expenditure, employment structure, education, health spending, and energy intensity interact to influence natural resource rents (% of GDP). (Šlaus and Jacobs, 2011; Rosendo Silva et al., 2018). By integrating quantitative indicators with a conceptual framework of human development and the evolution of consciousness, this study aims to identify the most influential drivers of sustainable transformation within the BRICS context.

Following this introduction, Section 2 outlines the theoretical foundations relevant to the sustainability. Section 3 reviews the existing body of literature and prior empirical studies in this domain. Section 4 details the fuzzy logic modeling framework. Sections 5 and 6 present the main findings and discussion. Finally, Sections 7 and 8 offer conclusion and practical recommendations for policymakers, while also highlighting directions for future research.

2. Theoretical Framework

Sustainability encompasses complex interactions among multiple forms of capital—natural, human, social, technological, and cultural—that collectively shape long-term development outcomes. This integrated perspective is particularly critical in BRICS countries (Brazil, Russia, India, China, and South Africa), where rapid economic growth and demographic dynamics intersect with pressing environmental and social challenges. In the Anthropocene, a period in which human activities dominate planetary systems, the advancement of human consciousness—through education, health investment, and cultural values—is increasingly recognized as a transformative force for sustainability (Wulf, 2022; Barna et al., 2020; Kim &

Go, 2020; Giarini, 1980; International Commission on Peace, 1994). This evolution entails a shift from purely materialistic development toward social and cognitive progress that fosters environmental stewardship and intergenerational equity. Education enhances cognitive capacities and collective decision-making, health underpins the vitality of human capital, and cultural values shape norms and behaviors that support sustainable lifestyles.

The economic theory proposed by Zhang et al. (2023) emphasizes the accumulation and deployment of capital—primarily physical capital—as the foundation of wealth creation. However, the authors also introduced the concept of human capital, defining it as the stock of knowledge, skills, and health accumulated by individuals that enhances productivity and innovation. Human capital is now widely recognized as a critical driver of sustainable development, as it shapes individuals' capacity for adaptation, creativity, and informed decision-making—capabilities that are essential for navigating complex socio-ecological systems. (Zhao et al., 2025; Jahanger et al, 2022; Akintoye & Adidu, 2008). Complementing human capital, social capital—defined as networks, trust, and norms facilitating collective action—plays a crucial role in sustainability by fostering cooperation and knowledge sharing across communities and institutions (Nguyen Thi & Vu Dinh, 2025; Ganda, 2022). Social capital enhances societal resilience by enabling collective responses to environmental risks and promoting equitable resource management. In the BRICS context, where cultural diversity and institutional heterogeneity are pronounced, leveraging social capital can help mediate conflicts and align development objectives with local values and traditions. (Nawaz et al., 2024). Natural capital, comprising the stock of natural resources and ecosystem services, remains the backbone of economic and social systems. The dependency of BRICS countries on natural resource rents as a percentage of GDP highlights the continued relevance of managing natural capital sustainably to avoid resource depletion and environmental degradation (Pathak et al, 2025; Giarini, 1980). This study's focus on natural resource rents as the dependent variable reflects an acknowledgment of both the direct and indirect impacts of economic activities on ecological assets. Furthermore, technological capital—encompassing innovation and investments in research and development—is essential for improving resource efficiency and fostering sustainable production systems. Technological advancement can mitigate environmental impacts and facilitate the transition from material-intensive growth toward more knowledge-based economies. (Effah et al., 2022; International Commission on Peace, 1994). However, the effectiveness of technology depends heavily on human capital, specifically education and health, which underpin mental adaptability and innovation capacity (Cui & Diwu, 2024)

Methodologically, the complexity and uncertainty inherent in sustainability policymaking necessitate approaches that can handle nonlinearity and imprecision. Fuzzy logic methods provide a flexible framework for integrating diverse indicators and capturing the ambiguous nature of human-environment interactions, enabling more nuanced analyses of sustainability drivers (Ahmad et al., 2019; International Commission on Peace, 1994). In summary, this theoretical framework integrates classical and contemporary perspectives on various forms of capital and human consciousness, emphasizing that sustainable development in BRICS countries is not solely determined by the exploitation of natural resources but is fundamentally driven by investments in human and social capital. The interactions among these forms of capital, shaped by cultural and technological factors, guide the trajectory of sustainability, highlighting the pivotal role of human choices and values in shaping development outcomes. Figure 1 illustrates the relationships between the studied variables and the dependent variable, natural resource rents.

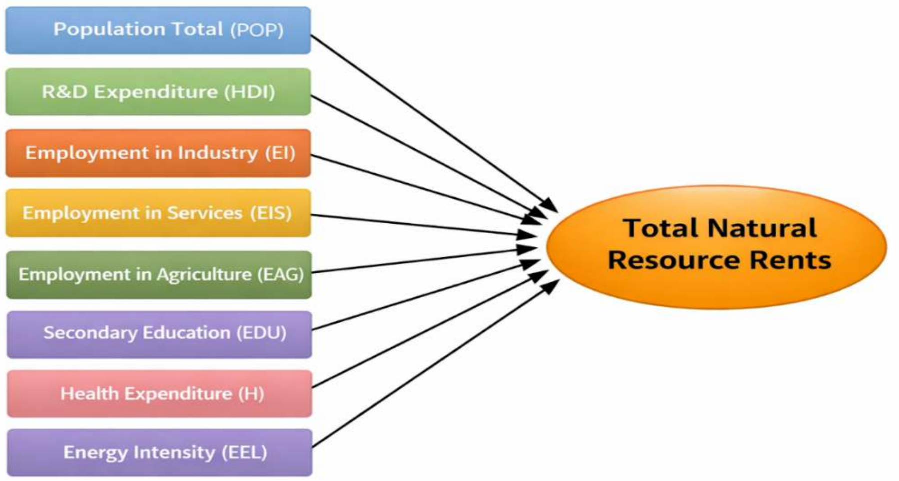


Fig 1. Conceptual framework illustrating the relationships between forms of capital and natural resource rents. This diagram is based on the conceptual synthesis of this study and previous research on human, social, technological, and natural capital influencing resource rents (e.g., Zhang et al., 2023; Wulf, 2022; Barna et al., 2020).

3. Literature Review

Sustainability research in the context of emerging economies, particularly BRICS countries, has increasingly emphasized the multifaceted roles of different forms of capital—natural, human, social, technological, and cultural—in shaping sustainable development trajectories. This section reviews significant contributions to the literature, focusing on empirical findings related to the determinants of sustainability, methodologies used, and the implications for policy. Li et al. (2015) and Ding et al. (2021) underscored the importance of capital accumulation for economic growth, primarily emphasizing physical capital. However, subsequent scholarship expanded this notion to include human and social capital as pivotal drivers of development. Lazuka & Jensen (2025) and Zeng & Punjwani (2025) introduced the concept of investment in human capital, highlighting education and health as critical elements enhancing labor productivity and economic performance. Kuzmin et al. (2023) further solidified this view by formalizing human capital theory, which has since been empirically linked to innovation and sustainable economic growth in developing countries.

The interplay between natural resource dependence and sustainability has been widely studied. Giarini (1980) emphasized the need for managing critical natural capital to maintain ecological resilience. Dietz and Neumayer (2007), Xu et al. (2022) differentiated between weak and strong sustainability, arguing for policies that preserve natural capital stocks rather than merely substituting them with human-made capital. In BRICS countries, natural resource rents constitute a significant share of GDP, posing challenges for resource management and environmental conservation. Social capital has emerged as a vital factor influencing sustainability outcomes. Nguyen Thi & Vu Dinh (2025) demonstrated how social networks and trust facilitate collective action, governance effectiveness and sustainable performance. Kumar et al. (2025) traced the conceptual history of social capital, underscoring its multidimensional nature. In BRICS contexts, social capital influences community resilience and equitable development, as supported by recent empirical work highlighting the role of social cohesion in environmental governance (Šlaus and Jacobs, 2011). Technological capital, reflected in research and development (R&D) expenditures and innovation capacity, is critical for decoupling economic growth from environmental degradation (International Commission on Peace, 1994; Bai et al., 2020). Recent studies show that investments in technology and education synergistically enhance energy efficiency and reduce carbon footprints in emerging economies (Ott & Doering, 2003; Elgin & LeDrew, 1997). The Anthropocene framework, introduced by Crutzen (2016) and expanded by Steffen et al. (2018), situates sustainability within the epoch where human actions dominate ecological processes. This underscores the necessity of advancing human consciousness and values to address global environmental challenges. Martinez-Fernandez et al. (2021) stressed that sustainability requires transcending conventional growth paradigms toward holistic socio-ecological well-being. Ekardt (2024) provided philosophical insights into the transformation of human consciousness as essential to sustainability transitions. Xiaoyang et al. (2022) investigated the impact of technological innovation, R&D, and energy intensity on CO_2 emissions using panel data from 36 OECD and 5 BRICS countries between 2005 and 2018. Employing both two-stage least squares (2SLS) and panel GMM methods, they found consistent and robust results. Their analysis revealed that while technological innovation and R&D are positively associated with CO_2 emissions, energy intensity is negatively related, highlighting the complex dynamics between development and environmental sustainability.

Methodologically, fuzzy logic approaches have been employed to capture the complexity and uncertainty inherent in sustainability assessments. Kucuk & Camgöz-Akdağ (2024), Ahmad et al. (2019) and recent applications in sustainability policy underscore the effectiveness of fuzzy logic in integrating diverse indicators and facilitating nuanced decision-making under uncertainty.

The Sustainability Assessment by Fuzzy Evaluation (SAFE) model, as developed by Andriantiatsaholiniaina et al. (2004), employs fuzzy logic reasoning and basic indicators of environmental integrity, economic efficiency, and social welfare to derive measures of human (HUMS), ecological (ECOS), and overall sustainability (OSUS). Their study confirms the primacy of human capital—through investments in education and health—in driving positive outcomes, and performs sensitivity analysis to identify the most important factors contributing to sustainable development. Chen et al. (2024) highlighted technological innovation as a critical lever for reducing energy intensity, reinforcing findings from earlier studies. Similarly, Huang et al. (2024) employed the Two Step System GMM methodology to examine the interplay between social capital and financial inclusion in fostering sustainable growth. Their study found that financial participation has a strong correlation with financial literacy and a significant influence on sustainable growth. Moreover, they highlighted that financial literacy acts as a crucial mediator, while social capital significantly moderates the relationship between financial inclusion and sustainable development, contributing valuable insights into the roles of financial and social factors in driving economic sustainability. Furthermore, Hu (2023) analyzed China's economic evolution amid demographic changes from 1990 to 2050, integrating multiple economic growth theories with empirical data. The study examined how aging population, urbanization, and family dynamics impact labor, demand, and productivity. Hu's work provides valuable insights into managing demographic transitions and their effects on sustainability, offering practical policy recommendations. Furthermore, Qasemi (2023) examined the impact of clean energy on environmental sustainability and economic growth. Using data from 132 experts in Kermanshah Province and analyzed through structural equation modeling, he showed that clean energy significantly enhances environmental preservation (57%) and economic growth (28%), with environmental protection further positively influencing economic growth (8%). The findings highlight the crucial role of clean energy in promoting sustainable development. GhoharShahi et al. (2024) also analyzed the dynamic policies for sustainable energy resource management based on the interlinkages among water, food, and energy resources using a system dynamics approach. The model was developed and simulated using data from South Khorasan Province with Vensim software. The results indicate that a combination of water and food demand management along with increased adoption of renewable energy (wind and solar) and improved irrigation efficiency represents the most effective sustainable energy management policy. In this context, variables such as renewable energy deployment, irrigation efficiency, and consumption pattern adjustments were shown to significantly enhance resource sustainability across energy, water, and food sectors.

Overall, the literature converges on the conclusion that sustainability in BRICS countries hinges on a holistic integration of multiple capitals, with human capital—especially education and health—playing a central role. The complexity of these interactions necessitates methodological approaches like fuzzy logic to guide effective policymaking under uncertainty. This body of research provides a robust theoretical and empirical foundation for the present study, which investigates the relationship between natural resource rents and various human development and economic structure variables in BRICS nations.

The innovation of this study lies in three key dimensions that distinguish it from prior research. First, by employing a fuzzy logic methodology, this work offers a simultaneous, interaction-based analysis of human, economic, and energy-related variables across BRICS countries—whereas most previous studies have tended to focus on a single or limited set of capital forms, such as human or natural capital. Second, this research introduces the concept of human consciousness and mental transformation as a critical driver of sustainability—an area that remains underexplored in the empirical literature. Third, the study presents a novel analytical model by integrating structural variables such as energy intensity and employment distribution across economic sectors with indicators of human development. This multidimensional approach provides a more comprehensive and realistic picture of sustainability dynamics in the Anthropocene era.

4. Methodology and data

4.1 Model Specification

This study utilizes a fuzzy logic-based model to analyze sustainability outcomes in BRICS countries—Brazil, China, Egypt, India, Iran, Russia, and South Africa—over the period from 1993 to 2024. The model's dependent variable is total natural resource rents (TNR), representing the economic dependence on natural capital. The set of independent variables includes population total (POP), research and development expenditure (HDI), employment in industry (EI), employment in services (EIS), employment in agriculture (EAG), secondary education (EDU), current health expenditure (H), and energy intensity level of primary energy (EEL), reflecting key aspects of human development, economic structure, and energy consumption. The specification is as follows:

$$TNR_{it} = \alpha + \beta_1.\mathrm{F}(POP_{it}) + \beta_2.\mathrm{F}(HDI_{it}) + \beta_3.\mathrm{F}(EI_{it}) + \beta_4.\mathrm{F}(EIS_{it}) + \beta_5.\mathrm{F}(EAG_{it}) + \beta_6.\mathrm{F}(EDU_{it}) + \beta_7.\mathrm{F}(H_{it}) + \beta_8.\mathrm{F}(EEL_{it}) + \varepsilon_t \quad (1)$$

where

TNR_{it} denotes total natural resource rents at time t for country i, referring to the countries under study. $\mathrm{F}(.)$ represents fuzzy logic transformations of the uncertain input variables population total (POP), research and development expenditure (HDI), employment in industry (EI), employment in services (EIS), employment in agriculture (EAG), secondary education (EDU), current health expenditure (H), and energy intensity level of primary energy (EEL), α is the intercept, β_i are the coefficients measuring the impact of each fuzzy variable, ε_t is the error term. The variables based on the studies Lazuka & Jensen (2025), Zeng & Punjwani (2025), Zhao et al. (2025), Bai et al. (2020), Šlaus and Jacobs (2011) can be defined and measured as follows:

- Population (POP): Total population is based on the de facto definition of population, which counts all residents regardless of legal status or citizenship.
- Research and development expenditure (HDI): Gross domestic expenditures on research and development (R&D), expressed as a percent of GDP.
- Employment in industry (EI): Employment is defined as persons of working age who were engaged in any activity to produce goods or provide services for pay or profit.
- Employment in services (EIS): Employment is defined as persons of working age who were engaged in any activity to produce goods or provide services for pay or profit. The services sector consists of wholesale and retail trade and restaurants and hotels; transport, storage, and communications; financing, insurance, real estate, and business services; and community, social, and personal services.
- Employment in agriculture (EAG): Employment is defined as persons of working age who were engaged in any activity to produce goods or provide services for pay or profit. The agriculture sector consists of activities in agriculture, hunting, forestry and fishing.

- Secondary education (EDU): Secondary pupils are the number of secondary students enrolled in general education programs.
- Current health expenditure (H): Level of current health expenditure expressed as a percentage of GDP. Estimates of current health expenditures include healthcare goods and services consumed during each year.
- Energy intensity level (EEL): Energy intensity level is the ratio between energy supply and gross domestic product measured at purchasing power parity. Energy intensity is an indication of how much energy is used to produce one unit of economic output.

Each variable is measured in its respective domain units, providing comprehensive inputs for modeling their impact on outcomes like TNR_{it} in a fuzzy logic framework. The data used are annual and collected from the World Bank website.

In addition, the data sources and supporting literature for each variable used in the model are explicitly reported in Table 1, ensuring transparency and consistency with prior empirical studies.

Table 1. Data Sources and Supporting Literature for Model Variables

Variable	Definition	Data Source	Supporting Literature
TNR	Total natural resource rents (% of GDP) (Dependent variable)	World Bank, World Development Indicators (WDI)	Fu & Liu (2023)
POP	Population, total	World Bank, WDI	(Šlaus and Jacobs, 2011; Hu, 2023)
HDI	Research and development expenditure (% of GDP)	World Bank, WDI	(Šlaus and Jacobs, 2011; Paula & Silva, 2021)
EI	Employment in industry (% of total employment)	World Bank, WDI	(Šlaus and Jacobs, 2011; Jiaduo et al., 2023; Zeng & Punjwani, 2025)

Variable	Definition	Data Source	Supporting Literature
EIS	Employment in services (% of total employment)	World Bank, WDI	(Šlaus and Jacobs, 2011; Jiaduo et al., 2023; Zeng & Punjwani, 2025)
EAG	Employment in agriculture (% of total employment)	World Bank, WDI	(Šlaus and Jacobs, 2011; Jiaduo et al., 2023; Zeng & Punjwani, 2025)
EDU	Secondary education (% gross)	World Bank, WDI	(Šlaus and Jacobs, 2011;Shang et al., 2023; Zhao et al., 2025)
H	Current health expenditure (% of GDP)	World Bank, WDI	(Šlaus and Jacobs, 2011; Ali et al., 2025; Lazuka & Jensen, 2025)
EEL	Energy intensity level of primary energy (MJ per $2017 PPP GDP)	World Bank, WDI	(Šlaus and Jacobs, 2011; Xiaoyang et al., 2022)

The channels through which these variables influence total natural resource rents (TNR) are discussed in continuation. Population size (POP) influences total natural resource rents by determining aggregate resource demand and consumption patterns, with larger populations potentially intensifying pressure on natural capital (Šlaus and Jacobs, 2011; Hu, 2023). Research and development expenditure (R&D, proxied here by HDI-related investment) facilitates technological innovation, resource-efficient production, and sustainable extraction methods, thereby potentially increasing the productivity and longevity of natural resource utilization (Šlaus and Jacobs, 2011; Paula & Silva, 2021). Employment composition across sectors—industry (EI), services (EIS), and agriculture (EAG)—affects resource dependency and environmental footprints, as industrial and agricultural activities are typically more resource-intensive, whereas service sector expansion may decouple economic growth from resource depletion (Šlaus and Jacobs, 2011; Jiaduo et al., 2023; Zeng & Punjwani, 2025). Secondary education (EDU) enhances human capital and awareness, promoting informed resource management and adoption of sustainable practices (Šlaus and Jacobs, 2011;Shang et al., 2023; Zhao et al., 2025). Current health expenditure (H) indirectly contributes by improving workforce productivity and societal resilience, which can influence the sustainable utilization of natural assets (Šlaus and Jacobs, 2011; Ali et al., 2025; Lazuka & Jensen, 2025). Finally, energy intensity of primary energy consumption (EEL) captures the efficiency of energy use in production and consumption; lower energy intensity reflects greater efficiency, which mitigates environmental pressures and preserves natural resource rents (Šlaus and Jacobs, 2011; Xiaoyang et al., 2022). Collectively, these channels illustrate the multifaceted economic, social, and technological mechanisms through which structural, human, and institutional factors shape sustainability outcomes as measured by total natural resource rents.

4.2. Methodology

Probabilistic regression was first introduced by Asai et al. (1982). Their model incorporated fuzzy coefficients and was proposed as a means for accurately modeling input–output data. The estimation of the fuzzy parameters of the model—represented as triangular fuzzy numbers—is obtained by solving a linear programming problem, where the objective function minimizes the sum of the widths of the coefficients. The corresponding constraints are defined such that the observed value of the dependent variable corresponds to a specific membership degree of the estimated fuzzy set. Since the membership function of fuzzy sets is often represented by probability distributions, this approach is referred to as probabilistic regression (Shapiro, 2005; Hojati et al., 2005). The initial approach of Asai et al. (1982) laid the foundation for subsequent studies in the field of fuzzy regression. In general, probabilistic regression methods are well-suited for modeling small datasets. They possess strong logical justification and do not rely on restrictive statistical assumptions. However, these methods are relatively sensitive to outliers. A key advantage of probabilistic regression methods is that they are fundamentally based on the principles and concepts of fuzzy mathematics. In the following sections, the fuzzy regression model and the procedural steps involved in its implementation are discussed. We begin with a brief overview of fuzzy regression and then explain the estimation process for asymmetric fuzzy regression. The fuzzy regression analysis proposed by Asai et al. (1982) defines the general form of the model with fuzzy coefficients as expressed in equation (2).

$$\tilde{Y} = f(x, A) = \tilde{A}_0 + \tilde{A}_1 x_1 + \tilde{A}_2 x_2 + \cdots + \tilde{A}_n x_n \tag{2}$$

Fuzzy coefficients corresponding to the variables x_n can be represented $\tilde{\mathrm{A}}_{\mathrm{n}} = (a_n, s_n)$. Accordingly, the general form of the membership function $\tilde{A}$ can be expressed as in equation (3), characterized by three parameters: the center a, the left width s^L, and the right width s^R (Asai et al., 1982):

$$\tilde{A}(\mathrm{x}) = \begin{cases} 1 - \frac{a-x}{s^L} & a - s^L \leq x \leq a \\ 1 - \frac{x-a}{s^R} & a < x \leq a + s^R \end{cases} \tag{3}$$

This membership function can also be represented in an alternative form. Specifically, the right width can be expressed in terms of the left width, such that $s^L = ks^R$is substituted into the above membership function. Here, k is a real and positive constant referred to as the kurtosis coefficient. Consequently, the asymmetric triangular fuzzy number $\tilde{A}$ can be described as $\tilde{A} = (a, s^L, k)_T$. In this case, the corresponding membership function $\tilde{A}$ is represented by equation (4).

$$\tilde{A}(x) = \begin{cases} 1 - \frac{a-x}{s^L} & a - s^L \leq x \leq a \\ 1 - \frac{x-a}{ks^R} & a < x \leq a + ks^R \end{cases} \tag{4}$$

In general, any asymmetric triangular fuzzy coefficient $\tilde{A}$ can be represented by its left width s^L, center a, and right width s^R. To estimate the parameters of the fuzzy regression model (3), two criteria are considered. First, the membership value of each $y_i$in $\tilde{Y}_i$ should be sufficiently large. Second, it should be ensured that the fuzzy model provides a good fit to the observed data (Asai et al., 1982). Accordingly, the goal is to identify a model such that the fuzzy output $\tilde{Y}$ for all values $\tilde{Y}_j$achieves a membership degree as large as h, i.e.,

$$\tilde{Y}_j(y_j) \geq h \quad , \quad i = 1,2 \ldots.,m \tag{5}$$

The fuzzy coefficients $\tilde{A}_i$ are determined such that the ambiguity of the fuzzy output $\tilde{Y}_j$is minimized. The steps for estimating fuzzy regression models with symmetric and asymmetric coefficients are summarized in Section A. (Shapiro, 2005).

A. Algorithm I: Steps of the Linear Programming Algorithm for Estimating Fuzzy Regression with Symmetric Coefficients

1. First, the objective function is calculated according to Equation (6).

$$Z = 2ms_0 + 2\sum_{i=1}^{n}(s_i \sum_{j=1}^{m} x_{ji}) \tag{6}$$

Here, x_{ji} denotes the jth observation of the ith variable.

2. To estimate the right width, the right-hand constraint is calculated according to Equation (7).

$$(1-h)s_0 + (1-h)\sum_{i=1}^{n}(s_0 x_{ji}) + a_0 + \sum_{i=1}^{n}(s_0 x_{ji}) \geq +y_{i,} \quad j = 1,2,\ldots.,m \tag{7}$$

3- To estimate the left width, the left-hand constraint is calculated according to Equation (8).

$$(1-h)s_0 + (1-h)\sum_{i=1}^{n}(s_0 x_{ji}) - a_0 - \sum_{i=1}^{n}(s_0 x_{ji}) \geq -y_{i,} \quad j = 1,2,\ldots.,m \tag{8}$$

4- The centers a_i, the right widths s_i^R, and the left widths $s_i^L$are calculated for a membership degree of 0.9, according to Equation (9).

$$f^c(\mathrm{x}) = a_0 + a_1 x_1 + \cdots + a_n x_n$$

$$f_s^L(\mathrm{x}) = s_0^L + s_1^L x_1 + \cdots + s_n^L x_n$$

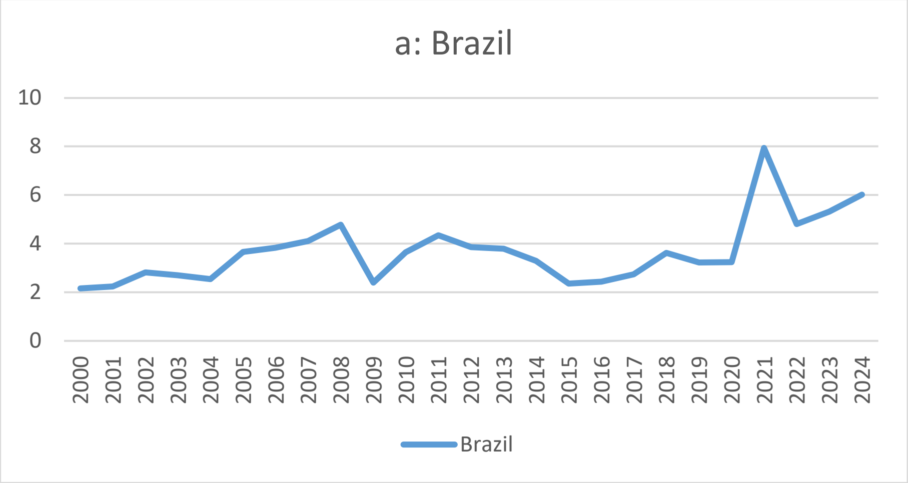
$$f_s^R(x) = s_0^R + s_1^R x_1 + \cdots + s_n^R x_n \tag{9}$$

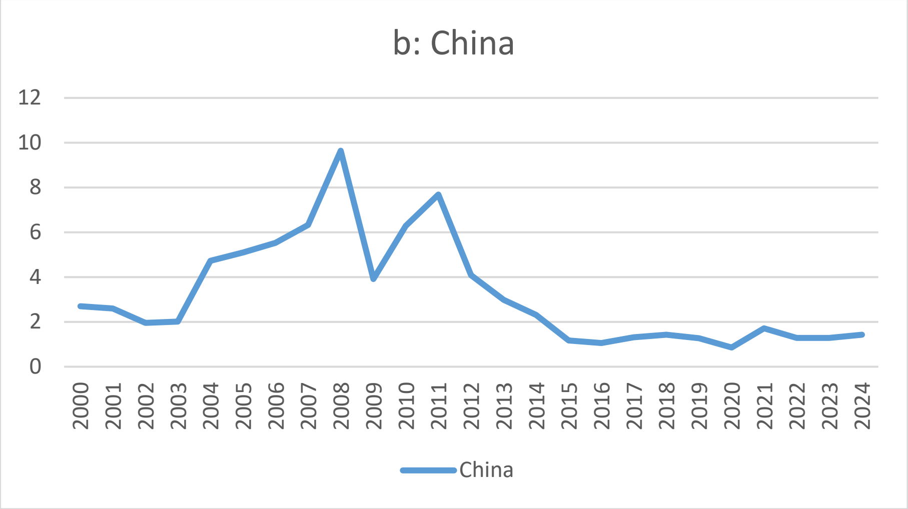
In the next section, the fuzzy regression model will be applied to the key variables affecting total natural resource rents in order to assess the impact of uncertainty.

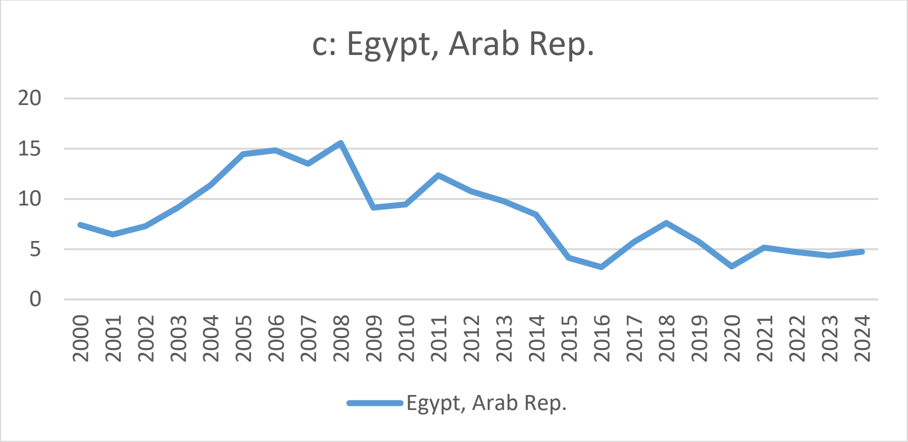
5. Findings

In this section, the fuzzy coefficients related to the methodological equations have been estimated, specifying the center value (average spread) and the fuzzy spreads (left and right spreads). The fuzzy range indicates the degree of fuzziness of the number; the larger this parameter, the higher the degree of fuzziness. In other words, fuzzy regression estimates an interval of possible values for all variables, whereas classical regression provides a single point estimate. Table 1 presents the results of the fuzzy regression in terms of right, average, and left spreads, illustrating the effects of explanatory variables on total natural resource rents. The explanatory variables include population, research and development expenditure, employment in industry, employment in services, employment in agriculture, secondary education, current health expenditure, and energy intensity level. Fig 1 presents a graphical representation of total natural resource rents (TNR) in the BRICS member countries.

Fig 1. Total Natural Resource Rents (TNR) trend in BRICS Countries



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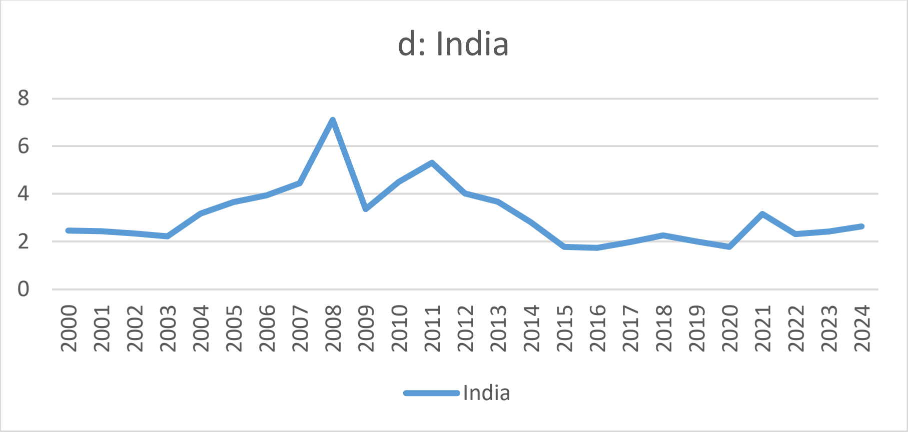
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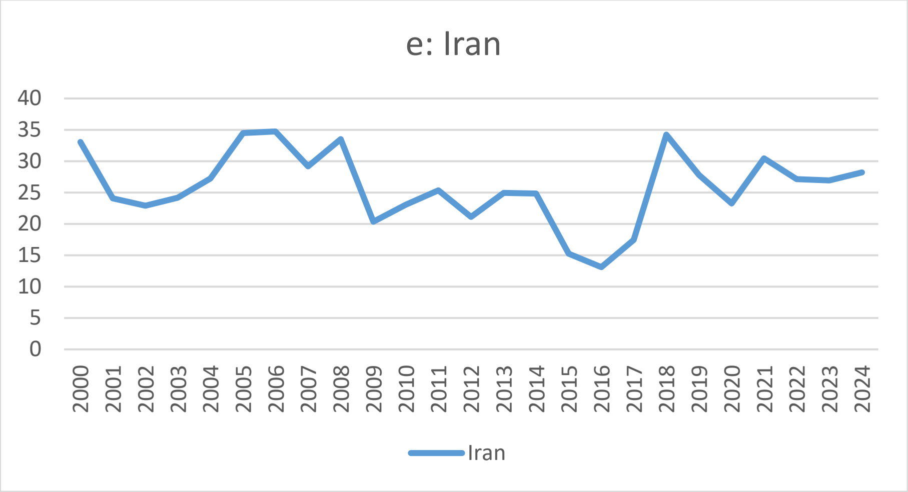
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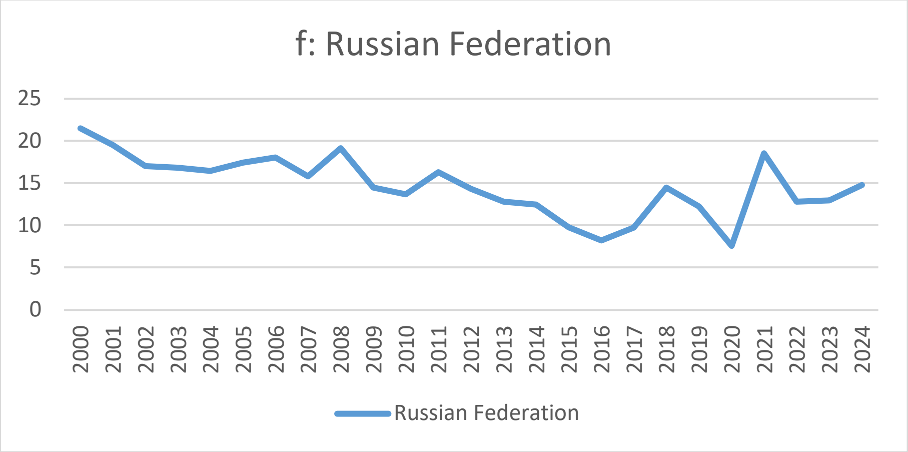
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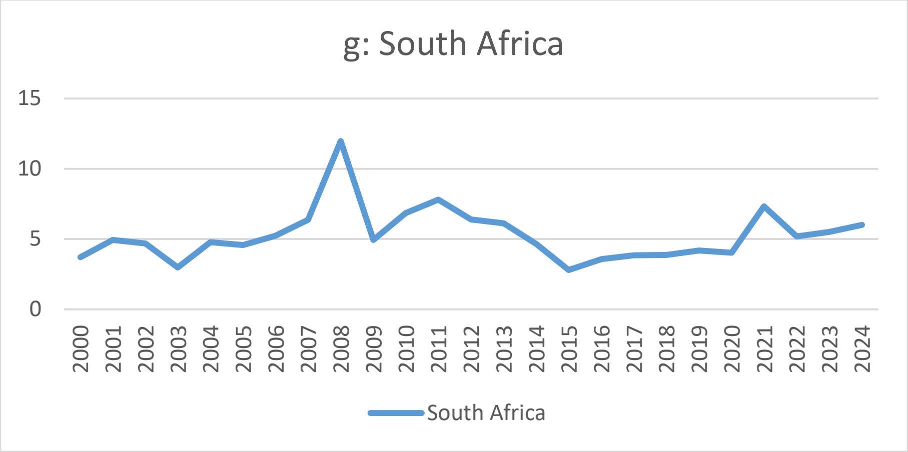

Fig 1. Illustrates distinct and divergent trajectories in total natural resource rents (TNR) across Brazil, China, Egypt, India, Iran, and the Russian Federation from 2000 to 2024, revealing substantial heterogeneity in resource dependence and economic structure. Brazil exhibits relatively stable TNR levels with a noticeable increase after 2020, indicating a continued but moderate reliance on natural resource revenues. China displays a clear long-term decline in TNR, reflecting structural transformation and reduced dependence on natural resources. Egypt, in contrast, records higher and more volatile TNR levels, highlighting its stronger reliance on resource-based revenues and greater exposure to external shocks. India's TNR trend reveals moderate fluctuations with a peak around 2008, followed by a gradual decline and stabilization post-2015, suggesting a shift toward economic diversification aligned with its expanding service and manufacturing sectors. Iran shows pronounced volatility, with sharp peaks in 2006, 2008, and 2018, and a significant dip around 2015—patterns that reflect its sensitivity to oil price dynamics, international sanctions, and domestic policy shifts. The Russian Federation demonstrates a long-term decline in TNR from 2000 to 2016, followed by a partial rebound in 2020 and 2022, likely driven by structural adjustments and geopolitical responses to stabilize resource income.

Additionally, South Africa presents a steadily rising TNR trend over the same period, indicating increasing reliance on natural resource revenues, possibly tied to mining sector expansion and commodity price cycles. Collectively, these patterns underscore the diverse pathways countries follow in managing resource wealth, shaped by domestic policy choices, global market exposure, and broader economic transitions. Table 2 displays the results from estimating the relevant relationship described in the methodology section to analyze the impact of effective factors on investment returns.

Table 2. Estimated Upper, Average, and Lower Bounds for Analyzing the Effects of Influential Variables on total natural resources rents with membership degree 0.9

countries	Variables	Lower Bound	Middle Bound	upper Bound
Brazil	HDI	-2.63e-09	5.31e-10	3.69e-09
	c	0.54	0.54	0.54
	POP	-1.88	1.26e-09	1.88
	EI	-0.48	0.019	0.52
	EIS	-4.46e-09	1.88e-09	8.23e-09
	EAG	-4.95e-09	6.59e-11	5.08e-09
	EDU	-1.97e-09	3.89e-10	2.75e-09
	H	-3.47	1.18e-09	3.47
	EEL	0.05	0.05	0.05
China	HDI	-2.65e-10	1.53e-11	2.96e-10
	c	-7.03e-10	1.68e-11	7.36e-10
	POP	-1.204e-09	2.12e-11	1.24e-09
	EI	0.028	0.028	0.028
	EIS	-4.79e-10	1.51e-11	5.10e-10
	EAG	-4.42e-10	4.15e-11	2.25e-10
	EDU	-5.63	0.609	6.85
	H	-0.309	8.65e-12	0.309
	EEL	0.171	0.171	0.171

countries	Variables	Lower Bound	Middle Bound	upper Bound
Egypt	HDI	-1.52e-10	1.65e-11	1.85e-10
	c	-3.66e-11	1.42e-11	6.508e-11
	POP	-4.51e-10	1.14e-11	4-74e-10
	EI	-4.14e-10	1.81e-11	4.51e-10
	EIS	-1.12e-10	1.52e-11	1.48e-10
	EAG	0.35	0.35	0.35
	EDU	-0.68	1e-11	0.68
	H	-1.94e-09	9.706e-12	1.96e-09
	EEL	-4.91	0.25	5.42
India	HDI	-1.62e-16	1.56e-17	1.93e-16
	c	1.45e-15	1.66e-15	1.87e-15
	POP	-1.22	0.63	2.49
	EI	-1.67	0.095	1.86
	EIS	-1.75e-16	2.11e-17	2.17e-16
	EAG	-3.13e-16	2.73e-17	3.68e-16
	EDU	-1.89e-16	1.302e-17	2.15e-16
	H	-2.46e-16	7.87e-18	2.62e-16
	EEL	-1.02	1.73e-17	1.02
Iran	HDI	4.52e-12	1.002e-11	1.55e-11
	c	0.23	0.23	0.23
	POP	0.211	0.211	0.211
	EI	0.227	0.227	0.227
	EIS	-5.07-12	5.64e-12	1.63e-11
	EAG	0.049	0.049	0.049
	EDU	-2.54	0.56	3.68
	H	-4.44	0.18	4.81
	EEL	1.23e-13	6.93e-12	1.37e-11
Russia	HDI	0.218	0.218	0.218
	c	-1.04	1.74e-12	1.04
	POP	-1.87	1.49e-12	1.87
	EI	0.67	0.67	0.67

countries	Variables	Lower Bound	Middle Bound	upper Bound
	EIS	-1.76	5.52e-08	1.76
	EAG	0.076	0.076	0.076
	EDU	-5.61e-11	4.43e-12	6.5e-11
	H	-1.39	0.23	1.86
	EEL	-5.07e-11	7.19e-12	6.51e-11
South Africa	HDI	-1.93e-14	2.03e-15	2.34e-14
	c	-2.9002e-14	3.39e-15	4.17e-14
	POP	-4.18	0.31	4.81
	EI	-2.061e-14	1.43e-15	2.34e-14
	EIS	0.083	0.083	0.083
	EAG	-0.81	0.19	1.19
	EDU	-2.74e-13	2.207e-15	2.78e-13
	H	-1.34e-12	3.58e-15	1.34e-12
	EEL	-0.126	0.036	0.199

Source: Calculations based on the current research

Under high uncertainty conditions (membership degree 0.9), the analysis of estimated upper bounds reveals significant variations in how key variables influence total natural resource rents across BRICS and other developing economies. In Brazil, the Human Development Index (HDI) shows a small effect on resource rents with an upper bound coefficient of 3.69e-09, while population (POP) has a wide-ranging effect from -1.88 to +1.88, indicating a strong two-sided influence. Employment in industry (EI) ranges from -0.48 to 0.52, suggesting a moderate and uncertain relationship with natural resource rents. Notably, employment in agriculture (EAG) fluctuates between -4.95e-09 to +5.08e-09, and education (EDU) also shows mixed effects, ranging from -1.97e-09 to +2.75e-09. Health expenditure (H) presents a broad effect, from -3.47 to +3.47, reflecting its substantial and ambiguous role in Brazil's resource-related economic outcomes. In China, the HDI ranges from -2.65e-

10 to +2.96e-10, indicating marginal influence. Interestingly, employment in industry (EI) remains constant at 0.028, reinforcing its consistent impact under uncertainty. However, education (EDU) shows a very wide range, from -5.63 to +6.85, indicating that human capital development affects resource rents, depending on governance and policy alignment. Health (H) also has a symmetrical effect from -0.309 to +0.309. In Egypt, the HDI has an upper bound of 1.85e-10, again reflecting minimal impact. Employment-related variables such as EI and EAG exhibit contrasting behavior — while EI remains negligible (±4.14e-10), EAG is stable at 0.35. The education (EDU) variable moves from -0.68 to +0.68, and energy intensity level (EEL) shows a strong swing from -4.91 to +5.42, highlighting the importance of energy intensity in managing resource wealth. In India, population and employment in industry again demonstrate notable effects. POP ranges from -1.22 to +2.49, and EI from -1.67 to +1.86, pointing to their dual role in either enhancing or degrading natural resource rents. Education (EDU) and health (H) have extremely small coefficients but still demonstrate symmetrical effects, suggesting potential latent impact over longer horizons. Energy intensity level (EEL) swings widely from -1.02 to +1.02. In Iran, HDI is throughout the range (4.52e-12 to 1.55e-11), while employment in industry (EI) holds a constant influence at 0.227. Education (EDU) and health (H) show significant swings — from -2.54 to +3.68 and -4.44 to +4.81, respectively — implying that improvements in these areas could yield considerable benefits in resource management if properly guided. Interestingly, EEL also shows a small trend (1.23e-13 to 1.37e-11), reinforcing the potential of Energy intensity. In Russia, employment in industry (EI) exhibits a strong and consistent effect at 0.67, while EIS (employment in services) ranges broadly from -1.76 to +1.76, indicating volatility in how employment in services affect resource rents. Population again plays a dual role (-1.87 to +1.87), and health (H) spans -1.39 to +1.86, both showing significant but uncertain effects. Other variables such as education (EDU) and EEL show very small effects. Lastly, in South Africa, population has one of the broadest ranges in the dataset, from -4.18 to +4.81,

reflecting the country's complex demographic-resource interaction. Employment in agriculture (EAG) ranges from -0.81 to +1.19, and EEL from -0.126 to +0.199, both suggesting employment in agriculture and energy intensity have variable effects on resource rents. Interestingly, HDI, EI, EDU, and H show extremely small coefficients, typically within the 10^-14 to 10^-13 range, suggesting their influence may be indirect or latent under high uncertainty. Across these countries, population (POP) and employment in industry (EI) emerge as the most consistently impactful variables on total natural resource rents, especially under conditions of high uncertainty. In countries like India, Russia, and South Africa, the dual nature of these effects indicates a strong sensitivity to demographic and energy-related shifts. Variables like education, health, and Energy intensity level demonstrate potential but vary significantly between countries, suggesting that effective governance and targeted investment are crucial to unlocking their positive effects on sustainability and economic returns from natural resources. Human capital, especially education and social awareness, is the key driver of sustainability, and its development is crucial for the sustainable future of BRICS. This study offers a novel approach to managing the complexities of sustainability policymaking by applying fuzzy logic. Finally, the results were consistent and in agreement with the findings of Li et al. (2015) and Ding et al. (2021), Lazuka & Jensen (2025), Bai et al. (2020), Šlaus and Jacobs (2011).

This study provides critical insights into the multifaceted drivers of sustainability within BRICS countries by emphasizing the pivotal role of human capital—particularly education and social awareness—in shaping sustainable development outcomes. The fuzzy logic analysis reveals complex interactions between natural resource dependency and broader socio-economic factors, underscoring that sustainability is not solely contingent on the availability of natural resources but heavily reliant on human consciousness and adaptive capacities. These findings resonate with prior theoretical and empirical work (Šlaus and Jacobs, 2011; Becker, 2002; Crutzen, 2016; Lazuka & Jensen, 2025), confirming that education and health investments enhance mental adaptability, innovation, and collective decision-making, all of which are crucial for navigating the uncertainties of the Anthropocene. In contrast to traditional economic growth models centered on material capital accumulation (Jahanger et al, 2022; Kim & Go, 2020; Becker, 2002), the study highlights a paradigm shift toward integrating social and cognitive dimensions of development. This transition reflects a growing recognition that effective sustainability strategies require reinforcing human and social capital to mediate the pressures imposed by natural resource exploitation and environmental degradation (Nawaz et al., 2024). Moreover, the employment structure analysis, linking sectoral labor distribution with sustainability, points to the importance of diversifying economies away from resource-intensive industries toward service and knowledge sectors. This aligns with global trends emphasizing technological innovation as a driver for reducing energy intensity and mitigating environmental impacts (Ott & Doering, 2003).

6. Concluding

This study underscores that advancing sustainability in BRICS countries fundamentally depends on enhancing human capital and consciousness. Education, health, and social awareness emerge as pivotal factors that shape a nation’s capacity for innovation, social cohesion, and responsible resource management. By applying fuzzy logic, the research effectively captures the inherent complexity and uncertainty in sustainability policymaking, allowing for a nuanced understanding of the interdependencies among economic, social, and environmental variables. These insights emphasize that sustainability trajectories are not determined solely by economic growth or resource availability but also by the deliberate cultivation of mental, social, and cultural capitals that foster collective responsibility and adaptive governance. Country-specific analyses reveal a diverse and often ambiguous influence of human capital and demographic variables on natural resource rents across BRICS nations. For instance, each country exhibits a distinct dominant variable with the highest upper bound value, indicating its strongest influence on the model. For Brazil, the variable H (3.47) shows the greatest impact, suggesting that health factors are most influential. In China, EDU (6.85) stands out as the dominant factor, highlighting education's major role. In Egypt, the variable EEL (5.42) has the highest value, implying that Energy intensity level contributes most significantly. For India, POP (2.49) dominates, meaning population has the strongest effect. In Iran, the variable H (4.81) is again the largest, emphasizing the significance of health or human development indicators. In Russia, EIS (1.76) is the highest, indicating the strong influence of employment in services. Finally, in South Africa, POP (4.81) shows the greatest magnitude, suggesting that population-related variables play the most critical role. Therefore, while education and health dominate in China and Iran respectively, population and structural factors are more influential in India, Russia, and South Africa. Ultimately, the findings advocate for a holistic and context-aware approach to sustainability in BRICS nations, recognizing that human capital development and conscious social choice are decisive forces shaping their sustainable futures. Policymakers must therefore prioritize education, health, and cultural values to unlock the latent potential of their populations and navigate the uncertainty embedded in resource-based economies. This approach not only aligns with but also extends existing literature by offering a methodological framework grounded in fuzzy logic to better address the complexity of sustainability policymaking in emerging markets. To advance sustainable development in Iran and other BRICS nations, prioritizing human capital is essential. Iran should invest in quality education that integrates sustainability literacy and critical thinking, fostering an adaptive and innovative society. Strengthening healthcare infrastructure is equally important to build a resilient workforce capable of addressing environmental and social challenges. Promoting social capital through participatory governance and inclusive dialogue among government, civil society, and industry will empower equitable resource management. Economic diversification away from energy-intensive industries toward knowledge- and service-based sectors can reduce environmental degradation and stimulate green innovation, leveraging Iran's educated population. Incorporating advanced analytical tools like fuzzy logic into policymaking will improve handling of the inherent complexity and uncertainty in sustainability issues. Additionally, integrating Iran's rich cultural values into sustainability programs can enhance environmental stewardship and collective responsibility. At a broader BRICS level, fostering regional and international cooperation, investing in sustainable infrastructure, renewable energy, and clean technologies are vital to reducing energy intensity and promoting economic diversification. Collective efforts in these areas will help balance economic growth with social well-being and ecological integrity, highlighting the critical role of conscious human choice and shared values in shaping a sustainable future.

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Author's contributions

All authors had contribution in preparing this paper.

Conflicts of interest

The authors declare no conflict of interest

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