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Investigating the Determinants of Ecological, Carbon Footprints and Natural Resources: Evidence from Asian Countries

Badanie czynników determinujących zasoby ekologiczne, ślad węglowy i zasoby naturalne: dowody z krajów azjatyckich

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Abstract
This study investigates the key drivers of environmental sustainability in 43 Asian economies from 1990 to 2023, emphasizing their implications for sustainable development, particularly in alignment with the United Nations Sustainable Development Goals (SDGs 7, 8, 9, 13, and 15). Using the Generalized Method of Moments (GMM), with robustness checks via the fixed effects model and Driscoll-Kraay standard error POLED OLS regression, findings reveal that improved macroeconomic management and foreign direct investment (FDI) significantly reduce ecological footprint, GHG emissions, and natural resource rents. This suggests that strengthening macroeconomic frameworks through the Country Policy and Institutional Assessment (CPIA) and attracting sustainable FDI can promote environmental sustainability and long-term resource conservation, supporting SDG 8 (Decent Work and Economic Growth) and SDG 9 (Industry, Innovation, and Infrastructure). Furthermore, individual internet usage negatively and significantly correlates with natural resource depletion and GHG emissions, indicating that digital expansion could contribute to sustainable environmental outcomes, in line with SDG 9. Additionally, GDP growth and investment are found to reduce natural resource depletion and GHG emissions while increasing natural resource rents, emphasizing the importance of policies that align economic growth with sustainability goals (SDG 8 & SDG 9). However, population growth exacerbates natural resource depletion and GHG emissions, highlighting demographic pressures as a critical sustainability challenge relevant to SDG 13 (Climate Action) and SDG 15 (Life on Land). Overall, our findings provide valuable insights for policymakers, emphasizing the need for integrated economic, technological, and environmental strategies to achieve sustainable development, particularly in addressing climate change (SDG 13), promoting responsible resource management (SDG 15), and ensuring affordable, sustainable energy solutions (SDG 7 – Affordable and Clean Energy).

Key words: ecological footprint, GHG emissions, natural resource rents, macroeconomic management, foreign direct investment, internet usage, GDP growth, sustainable development

Streszczenie
W niniejszym artykule zbadano kluczowe czynniki zrównoważonego rozwoju środowiskowego w 43 krajach azjatyckich w latach 1990–2023, podkreślając ich implikacje dla zrównoważonego rozwoju, w szczególności w zgodzie z Celami Zrównoważonego Rozwoju Organizacji Narodów Zjednoczonych (SDGs 7, 8, 9, 13 i 15). Korzystając z uogólnionej metody momentów (GMM) z kontrolami solidności za pomocą modelu efektów stałych i regresji standardowego błędu Driscolla-Kraaya POLED OLS, wyniki pokazują, że ulepszone zarządzanie makroekonomiczne i bezpośrednie inwestycje zagraniczne (BIZ) znacznie zmniejszają ślad ekologiczny, emisje gazów cieplarnianych i renty zasobów naturalnych. Sugeruje to, że wzmocnienie ram makroekonomicznych poprzez ocenę polityki krajowej i instytucjonalnej (CPIA) oraz przyciąganie zrównoważonych BIZ może promować zrównoważony rozwój środowiskowy i długoterminową ochronę zasobów, wspierając SDG 8 (Godna praca i wzrost gospodarczy) i SDG 9 (Przemysł, innowacje i infrastruktura). Ponadto indywidualne korzystanie z Internetu negatywnie i znacząco koreluje z wyczerpywaniem się zasobów naturalnych i emisjami gazów cieplarnianych, co wskazuje, że ekspansja cyfrowa może przyczynić się do zrównoważonych wyników środowiskowych, zgodnie z SDG 9. Stwierdzono też, że wzrost PKB i inwestycje zmniejszają wyczerpywanie się zasobów naturalnych i emisje gazów cieplarnianych, a jednocześnie zwiększają renty zasobów naturalnych, podkreślając znaczenie polityk, które dostosowują wzrost gospodarczy do celów zrównoważonego rozwoju (SDG 8 i SDG 9). Jednak wzrost populacji nasila wyczerpywanie się zasobów naturalnych i emisje gazów cieplarnianych, podkreślając presję demograficzną jako krytyczne wyzwanie dla zrównoważonego rozwoju istotne dla SDG 13 (Działania na rzecz klimatu) i SDG 15 (Życie na lądzie). Ogólnie rzecz biorąc, nasze ustalenia dostarczają cennych spostrzeżeń decydentom, podkreślając potrzebę zintegrowanych strategii ekonomicznych, technologicznych i środowiskowych w celu osiągnięcia zrównoważonego rozwoju, w szczególności w zakresie przeciwdziałania zmianie klimatu (SDG 13), promowania odpowiedzialnego zarządzania zasobami (SDG 15) i zapewniania niedrogich, zrównoważonych rozwiązań energetycznych (SDG 7 – Przystępna cenowo i czysta energia).

Słowa kluczowe: ślad ekologiczny, emisje gazów cieplarnianych, renty zasobów naturalnych, zarządzanie makroekonomiczne, bezpośrednie inwestycje zagraniczne, korzystanie z Internetu, wzrost PKB, zrównoważony rozwój

1. Introduction

In the face of rising global environmental challenges, understanding the factors that influence ecological sustainability, carbon emissions, and natural resource utilization has become increasingly crucial. This study focuses on investigating these determinants within the context of Asian countries, a region that encompasses a diverse array of economies, cultures, and ecosystems. As home to approximately 60% of the world's population and some of the fastest-growing economies globally, Asia plays a pivotal role in shaping the trajectory of global environmental health and resource management (Mohamed et al., 2024; United Nations, 2023).

The concepts of ecological footprint, carbon footprint, and natural resource management are central to this investigation. The ecological footprint, first introduced by Wackernagel and Rees (1996), measures human demand on nature, representing the amount of biologically productive land and sea area necessary to supply the resources a human population consumes and to assimilate associated waste. Carbon footprint, a subset of the ecological footprint, specifically quantifies the total greenhouse gas emissions caused directly and indirectly by an individual, organization, event, or product (Adeleye et al., 2021; Osabohien et al., 2024; Osabohien et al., 2024; Wiedmann & Minx, 2008). Natural resource management, meanwhile, encompasses the sustainable utilization of major natural resources such as land, water, air, minerals, forests, fisheries, and wild flora and fauna (OECD, 2011).

Asia's rapid economic growth and urbanization over the past few decades have led to significant increases in energy consumption, carbon emissions, and pressure on natural resources. According to the Asian Development Bank (2021), the region's share of global carbon dioxide emissions increased from 25% in 1990 to 47% in 2019. This dramatic rise underscores the urgency of understanding the underlying factors driving these trends and identifying potential pathways towards more sustainable development.

The determinants of ecological and carbon footprints, as well as natural resource use, are complex and multifaceted. They span economic, social, technological, and policy domains. Previous studies have identified several key factors influencing these environmental indicators such economic Growth - the relationship between economic development and environmental degradation has been extensively studied, often through the lens of the Environmental Kuznets Curve (EKC) hypothesis. This theory suggests that environmental degradation initially increases with economic growth but eventually decreases as economies reach higher levels of development (Grossman & Krueger, 1995). However, empirical evidence for the EKC has been mixed, particularly in the context of developing countries (Mohamed et al., 2024; Stern, 2004).

Other indicator examined in previous studies include population dynamics - Population growth and urbanization are significant drivers of resource consumption and environmental pressure. In Asia, rapid urbanization has led to increased energy demand, land-use changes, and waste generation (Poumanyvong & Kaneko, 2010). Furthermore, Advancements in technology can have both positive and negative impacts on environmental indicators. While some technologies improve energy efficiency and reduce emissions, others may lead to increased resource extraction and consumption (York et al., 2003). Trade and Globalization play a major role, because, international trade can affect a country's ecological and carbon footprints through various mechanisms, including the pollution haven hypothesis and the displacement of environmental impacts through global supply chains (Peters et al., 2011).

The effectiveness of environmental policies and regulations is closely tied to the quality of institutions and governance structures. Corruption, weak enforcement, and lack of transparency can undermine efforts to manage natural resources sustainably and reduce environmental impacts (Lau et al., 2014). In the Asian context, these determinants interact in unique ways, shaped by the region's diverse economic landscapes, governance structures, and cultural traditions. For instance, China's rapid industrialization and urbanization have led to substantial increases in energy consumption and carbon emissions, while also driving technological innovations in renewable energy (Liu et al., 2019). India, on the other hand, faces the challenge of balancing economic development with environmental sustainability, particularly in the context of its large and growing population (Ghosh, 2019).

Southeast Asian countries like Indonesia and Malaysia grapple with issues of deforestation and land-use change, which significantly impact their ecological footprints and biodiversity (Austin et al., 2019). Meanwhile, highly developed economies such as Japan and South Korea have made strides in energy efficiency and circular economy practices, offering potential models for sustainable development in the region (Sang-Hyup, 2020).

The diversity of experiences across Asian countries provides a rich ground for comparative analysis and offers valuable insights into the complex interplay of factors shaping ecological and carbon footprints, as well as natural resource management practices. Despite a growing body of literature on environmental sustainability in Asia, several gaps remain in our understanding of the determinants of ecological and carbon footprints, as well as natural resource use in the region. First, while numerous studies have examined these issues at the national level, there is a need for more comprehensive analyses that account for the heterogeneity across Asian countries and subregions. Second, the dynamic nature of these determinants, particularly in the context of rapidly changing economies and technologies, calls for updated and longitudinal studies.

The structure of this paper is as follows: Following this introduction, Section two provides a detailed literature review, examining existing research on the determinants of ecological and carbon footprints, as well as natural resource use, with a focus on studies conducted in Asian contexts. Section three outlines the theoretical framework and methodology employed in this study. Section four presents the empirical results and analysis. Section five discusses the implications of the findings for policy and practice and concludes the paper, summarizing key insights and suggesting directions for future research.

2. Literature Review

This literature review examines a collection of studies focusing on the interplay between economic development, environmental sustainability, and climate change. The selected works span a range of topics, including the Environmental Kuznets Curve (EKC) hypothesis, drivers of energy consumption and carbon emissions, deforestation, urbanization impacts, and policy responses to environmental challenges. By analysing these diverse sources, we aim to provide a comprehensive understanding of the current state of research in environmental economics and sustainability.

The Environmental Kuznets Curve (EKC) hypothesis, which posits an inverted U-shaped relationship between economic development and environmental degradation, is a central theme in several of the reviewed studies. Grossman and Krueger (1995) provide one of the seminal works on the EKC. Their study examines the relationship between per capita income and various environmental indicators, finding evidence for the EKC in some pollutants. They suggest that as countries develop, they initially experience increased environmental degradation, but beyond a certain income threshold, environmental quality begins to improve. However, Stern (2004) challenges the universal applicability of the EKC. His critical review argues that the EKC hypothesis may not hold for all environmental indicators, particularly for more aggregate measures of environmental impact. Stern emphasizes the importance of considering factors such as international trade, which can lead to the displacement of pollution from developed to developing countries. Recent studies enhance understanding of environmental sustainability drivers. Xu et al. (2025) highlight green finance's role in inclusive growth, while Li and Li (2023) show AI reduces 5G emissions. Shang and Luo (2021) support decoupling strategies, Sohel et al. (2023) emphasize reforestation, and Wu et al. (2025) contribute forecasting insights.

Lau et al. (2014) investigate the EKC hypothesis in the context of Malaysia, incorporating the roles of foreign direct investment (FDI) and trade. Their findings support the existence of an EKC for carbon emissions in Malaysia, with FDI and trade playing significant roles in shaping this relationship. This study highlights the importance of considering country-specific factors and international economic interactions when examining the EKC.

Several studies in this review focus on identifying and analyzing the drivers of energy consumption and carbon emissions across different countries and regions. Ghosh (2019) examines the drivers of energy consumption in India, with a particular focus on carbon emissions and urbanization. The study employs empirical methods to investigate the relationships between these factors, finding that urbanization and economic growth significantly influence energy consumption and carbon emissions in India. This research underscores the complex interplay between development, urbanization, and environmental impacts in rapidly growing economies.

Zhang and Cheng (2009) analyze the relationships between economic growth, energy consumption, and carbon emissions in China. Their study employs advanced econometric techniques to establish causal links between these variables, providing insights into the dynamics of China's energy-intensive economic growth and its environmental consequences. Liu et al. (2015) offer a revised estimate of carbon emissions from fossil fuel combustion and cement production in China. Their work highlights the challenges in accurately measuring and reporting carbon emissions, especially in rapidly industrializing countries. The study's findings have significant implications for global carbon accounting and climate change mitigation efforts.

Peters et al. (2011) investigate the growth in emission transfers via international trade from 1990 to 2008. Their research reveals the importance of considering consumption-based emissions accounting, as opposed to production-based measures. This study demonstrates how international trade can lead to the displacement of emissions from developed to developing countries, complicating efforts to reduce global carbon emissions. The relationship between urbanization and environmental impact is another key theme explored in several of the reviewed studies. Poumanyvong and Kaneko (2010) conduct a cross-country analysis to examine whether urbanization leads to less energy use and lower CO_2 emissions. Their findings challenge the notion that urbanization necessarily results in improved environmental outcomes. The study suggests that the impact of urbanization on energy use and emissions varies across different levels of development, highlighting the need for nuanced policy approaches. Austin et al. (2019) focus on the drivers of deforestation in Indonesia, a country experiencing rapid urbanization and economic development. Their research identifies key factors contributing to forest loss, including agricultural expansion and infrastructure development. This study emphasizes the importance of considering local and regional factors when examining the environmental impacts of development.

Several of the reviewed works discuss policy responses to environmental challenges and strategies for promoting sustainable or *green* growth. The OECD (2011) report *Towards Green Growth* provides a comprehensive framework for integrating economic and environmental policies. The report argues for the need to transition to a more sustainable economic model that promotes growth while preserving natural capital. It offers policy recommendations across various sectors, emphasizing the potential for green innovation to drive economic development. The Asian Development Bank (2021) report focuses on financing a green and inclusive recovery in the wake of the COVID-19 pandemic. This study highlights the opportunities and challenges in aligning economic recovery efforts with environmental sustainability goals in the Asian context. It emphasizes the role of green finance and sustainable infrastructure in promoting resilient economic growth.

Sang-Hyup (2020) examines South Korea's Green New Deal, providing insights into how a developed Asian economy is approaching the transition to a more sustainable economic model. The study discusses the policy measures and investments planned under this initiative, offering lessons for other countries considering similar green growth strategies. The reviewed studies employ a variety of methodological approaches and analytical tools to examine environmental and economic relationships. York et al. (2003) introduce and discuss analytical tools such as STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology), IPAT (Impact = Population × Affluence × Technology), and ImPACT for unpacking the driving forces of environmental impacts. These tools provide frameworks for analysing the complex interactions between demographic, economic, and technological factors in driving environmental change.

Wiedmann and Minx (2008) offer a detailed examination of the concept of *carbon footprint*, providing a clear definition and discussing methodological approaches for its calculation. This work is crucial for understanding and standardizing measures of environmental impact, particularly in the context of climate change mitigation efforts. Wackernagel and Rees (1996) introduce the concept of the *ecological footprint*, which has become a widely used measure of human impact on the environment. Their work provides a framework for assessing the sustainability of human activities by comparing resource consumption with the Earth's biological capacity to regenerate those resources.

Some of the reviewed studies offer broader theoretical perspectives on environmental change and sustainability, incorporating social and behavioural dimensions. Shove (2010) critiques dominant approaches to climate change policy, arguing for the need to move beyond individualistic models of behaviour change (the ABC – Attitude, Behaviour, Choice model). This work emphasizes the importance of considering social practices and systemic factors in addressing environmental challenges, offering a more holistic perspective on sustainability transitions. The United Nations (2023) World Population Prospects report provides crucial demographic data and projections that have significant implications for environmental sustainability. While not focused exclusively on environmental issues, this report offers essential context for understanding the long-term challenges of sustainable development in the face of global population growth and demographic shifts.

Mohamed et al. (2024) revisit the Environmental Kuznets Curve (EKC) hypothesis, which posits that environmental degradation initially increases with economic growth, but eventually decreases as countries develop and adopt cleaner technologies. The study focuses on the role of renewable energy in reducing carbon emissions and ecological footprint in power generation. Their findings reveal that renewable energy consumption does contribute to lower emissions and a smaller ecological footprint, but the impact is more significant in countries with higher income levels and better institutional quality.

Degbedji et al. (2024) examine the role of institutional quality in promoting green economic growth within the West African Economic and Monetary Union (WAEMU). The authors argue that strong institutions are necessary for fostering an environment conducive to green growth, which integrates economic development with environmental sustainability. Their analysis reveals that countries with higher institutional quality are better equipped to implement green policies, attract investment in renewable energy, and ensure environmental protection. Osabohien (2024) addresses the intersection of nutrition and Sustainable Development Goal (SDG) 15, which focuses on preserving terrestrial ecosystems. The study discusses how unsustainable land use practices, including deforestation and over-farming, negatively impact food security and nutrition outcomes.

Sahan et al. (2025) conduct a systematic review of the literature on green human resource management (GHRM) and its impact on energy-saving behaviour and environmental performance. The authors argue that GHRM practices – such as training employees in energy conservation techniques, promoting eco-friendly workplace behaviours, and incorporating sustainability into corporate culture – can significantly enhance environmental performance. Their review finds that organizations that adopt GHRM practices not only reduce their ecological footprint but also enjoy long-term economic benefits.

3. Methodology

The study is conducted within a framework aimed at testing the relationship between ecological footprint, GHG emissions, natural resources, and CPIA macroeconomic management rating, Gross Fixed Capital Formation (GFCF), Individuals using the Internet (TEC), Combustible Renewables and Waste (CRW), Trade Openness (TOP), and Foreign Direct Investment (FDI) as indicated in the equations.

This study refers to the following Sustainable Development Goals (SDGs): 7 – Affordable and Clean Energy, 8 – Decent Work and Economic Growth, 9 – Industry, Innovation and Infrastructure, 13 – Climate Action, 15 – Life on Land.

3.1. Theoretical framework and model Specification

This study utilizes a reference framework to construct a theoretical model linking environmental sustainability to its potential determinants and SDGs. The model evaluates the influence of macroeconomic management, technology usage, renewable energy, investment, trade openness, and foreign direct investment on environmental sustainability. This empirical study uses per capita ecological footprint, GHG emissions, and natural resource rents as measures of environmental sustainability. The reference model is presented as follows:

$$DE_{it} = \alpha_{it} P_{it}^{\beta_1} A_{it}^{\beta_2} T_{it}^{\beta_3} \varepsilon_{it} \quad (1)$$

Where DE, represents environmental sustainability P indicates population, A signifies economic growth, and T reflects technological advancement. The indices i and t represent countries and time periods, respectively. Equation 1 can be converted into a natural logarithmic form as follows:

$$lnDE_{it} = \alpha_{it} + \beta_1 lnP_{it} + \beta_2 lnA_{it} + \beta_3 lnT_{it} + \varepsilon_{it} \quad (2)$$

Using the current theoretical frameworks, we propose the following study model:

$$lnQE_{it} = \alpha_{it} + \beta_1 lnCPIA_{it} + \beta_2 lnGFCF_{it} + \beta_3 lnTEC_{it} + \beta_4 lnCRW_{it} + \beta_5 lnTOP_{it} + \beta_6 lnGDP_{it} + \beta_7 lnPOP_{it} + \beta_8 lnFDI_{it} + \varepsilon_{it} \quad (3)$$

3.2. Methods

3.2.1. The Generalized Method of Moments (GMM)

The analysis of the effects of macroeconomic management, renewable energy and waste, foreign direct investment, technology, trade openness, population, GDP growth, and investment on environmental sustainability, which relates to SDGs 7, 8, 9 and 15, presents several challenges. First, there is the problem of omitted variables and unobservable factors. For example, GDP growth can simultaneously affect the ecological footprint, greenhouse gas emissions (SDG 13), and natural resource rents. There may also be reverse causality, where environmental sustainability can influence GDP growth, CPIA macroeconomic management, and foreign direct investment. To address these issues, we use the Generalized Method of Moments (GMM) adapted for dynamic panel data. This method is based on the work of Roodman (2009a), which is an extension of that by Arellano and Bover (1995).

Indeed, three main reasons motivate our choice of the GMM. First, GMM is suitable for assessing whether past environmental quality is related to current environmental quality, thereby explaining the persistence of environmental quality in Asian countries. Second, to address the issue of endogeneity, the GMM approach is well-suited. Third, the number of observations exceeds the number of periods for each country. In this paper, there are thirty-four periods (1990-2023) for 45 countries. Following the study by Asongu and Odhiambo (2020), we have chosen the two-step procedure of the GMM technique with robust standard errors to ensure and control for heteroscedasticity issues. It is important to highlight that the system GMM approach has been used in several studies on growth (Bhattacharya et al., 2016). For this purpose, we consider model (3) as a dynamic panel model.

$$lnDE_{it} = \alpha_0 + \beta_0 lnDE_{it-1} + \beta_1 lnCPIA_{it} + \beta_2 lnGFCF_{it} + \beta_3 lnTEC_{it} + \beta_4 lnCRW_{it} + \beta_5 lnTOP_{it} + \beta_6 lnGDP_{it} + \beta_7 lnPOP_{it} + \beta_8 lnFDI_{it} + \eta_i + \xi_t + \varepsilon_{it} \quad (4)$$

Where $DE_{i,t-1}$ is the quality of environment of last year, ξ_t is the time constant, η_i is the country-specific effect.

3.2.2. The fixed effects model (FEM)

Fixed effects models are used for controlling unobserved heterogeneity when heterogeneity is constant over time and correlated with the independent variables (Greene, 2002; LaMotte, 1983). If there are omitted variables, and the variables are correlated with the variables in the model, then fixed effects models may provide a means to control for omitted variable bias. Fixed effects model is a primary default model for establishing causal relationship with panel data (Imai & Kim, 2016). The FEM is represented as:

$$lnDE_{it} = \alpha_i + \beta_1 lnCPIA_{it} + \beta_2 lnGFCF_{it} + \beta_3 lnTEC_{it} + \beta_4 lnCRW_{it} + \beta_5 lnTOP_{it} + \beta_6 lnGDP_{it} + \beta_7 lnPOP_{it} + \beta_8 lnFDI_{it} + \varepsilon_{it} \quad (5)$$

Where, $\alpha_i = z_i'\alpha$ for all the observable effects.

3.2.3. POLED OLS Regression with Driscoll-Kraay Standard Errors

This model allows for robust estimates in contexts where errors may exhibit complex correlations across time and observations. It adjusts standard errors to account for issues of autocorrelation and heteroscedasticity. The POLED OLS Regression model with Driscoll-Kraay Standard Errors is presented as follows:

$$lnDE_{it} = \alpha + \beta_1 lnCPIA_{it} + \beta_2 lnGFCF_{it} + \beta_3 lnTEC_{it} + \beta_4 lnCRW_{it} + \beta_5 lnTOP_{it} + \beta_6 lnGDP_{it} + \beta_7 lnPOP_{it} + \beta_8 lnFDI_{it} + \varepsilon_{it} \quad (6)$$

4. Data, Result and Discussion

4.1. Summary Statistics and Correlation Analysis

Our study covers the period from 1990 to 2023 for Asian countries. Only countries with a complete dataset were included in the study. The data used is sourced from the World Bank Development Indicators (WDI) (Table 1), while the summary statistics of the variables is presented in table 2. The dependent variables are the ecological footprint, GHG emissions, and natural resource rents, measured respectively by Adjusted Savings: Natural Resources Depletion as a percentage of GNI; CO_2 emissions in kg per PPP $ of GDP, and Total Natural Resources Rents as a percentage of GDP. Net foreign direct investment inflows, measured in US dollars, are drawn from the WDI and supported by the studies of Kastratović, R. (2023); Ofori and al., (2021), Sahoo and Dash (2022), and Alnafissa et al. (2022). On average, the value of foreign direct investment is 105,364.7 (Table 2), with minimum and maximum values of -8,860,851 and 3.88e+07, respectively (See table 2). The expected sign is positive, indicating that foreign direct investment improves environmental quality.

The proxy for information and communication technology (ICT) is the number of individuals using the internet as a percentage of the population, obtained from the WDI and supported by Ofori and al., (2021) and Oyelami et al. (2022). The average value for ICT is 24.43, ranging from 0 to 100. It is assumed that internet users promote environmental sustainability. Trade openness is captured by the ratio of exports plus imports divided by GDP, sourced from the WDI. The variable is supported by Kastratović, R. (2023); Ofori and al., (2021) and Alnafissa et al. (2022), with an average value of 4.19e+11, while it ranges between 46.71 and 1.79e+13.

Table 1. Variables used and there measurement and sources, source: Authors' computation

Variable	Description	Source
Dependent Variables (QE)		
NRD CFP NRR	Adjusted savings: natural resources depletion (% of GNI CO_2 emissions (kg per PPP $ of GDP) Total natural resources rents (% of GDP)	World Development Indicators (WDI)
Independent Variables		
FDI	Foreign direct investment, net inflows (% of GDP)	World Development Indicators (WDI)
CPIA	CPIA macroeconomic management rating (1=low to 6=high)	World Governance Indicators (WGI)
ICT	Individuals using the Internet (% of population)	World Development Indicators (WDI)
TOP	Trade (% of GDP)	World Development Indicators (WDI)
CRW	Combustible renewables and waste (% of total energy)	World Development Indicators (WDI)
GDP	GDP (current US$)	World Development Indicators (WDI)
POP	Population, total	World Development Indicators (WDI)

Table 2. Summary Statistics, source: Authors' computation

	Total		**Central Asia**		**East Asia**		**South Asia**		**Southeast Asia**		**West Asia**	
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Variables	**Mean [SD]**	**Min (max)**	**Mean [SD]**	**Min (max)**	**Mean [SD]**	**Min (max)**	**Mean [SD]**	**Min (max)**	**Mean [SD]**	**Min (max)**	**Mean [SD]**	**Min (max)**
NRD	5.91 [7.79]	0 (45.48)	9.39 (9.28)	0.24 (45.48)	2.36 3.91	0.00 18.48	1.11 1.53	0 8.66	5.63 6.91	0 29.47	8.71 8.93	0 38.09
cpiamm	3.65 (0.76)	1 (5.5)	3.94 (0.41)	3 (4.5)	3.4 0.33	3 4	3.43 0.70	1 4.5	3.91 0.75	1.5 5.5	3.82 1.10	1.5 5.5
GFCF	25.14 (9.26)	0.73 (70.54)	25.02 (8.91)	6.29 (51.93)	31.25 6.49	17.79 48.41	27.79 12.54	11.45 70.54	25.94 7.02	10.46 43.58	21.74 8.00	0.73 57.71
TECH	24.43 (20.84)	0 (100)	16.53 (24.99)	0 (92.29)	32.50 35.98	0 97.57	11.46 18.33	0 85.76	26.10 29.98	0 98.08	29.52 33.58	0 100
CRW	11.77 (14.79)	0 (75.36)	13.81 (16.11)	0.02 (75.36)	4.77 8.21	0.01 42.21	1.60 1.61	0.00 7.94	7.98 8.61	0.00 38.94	19.71 17.17	0 67.443
TOP	4.19 e+11 1.51e+12	46.71 (1.79e+13)	3.37e+0 5.51e+10	3.67 e +7 2.61e + 11	2.97e+12 3.91e+12	7.68e+8 1.79e+13	2.49e+11 6.05e+11	45.71 3.55e+12	1.81e +11 2.35e +11	1.40e+09 1.37e+12	1.07 e + 11 1.65 e + 11	4.08e+ 8 1.1 e+1 2
GDP	9451.03 (14741.69)	-20.73 (9804 1.36)	2561.74 (3178.43)	137.18 (13890.63)	16189.32 15424.22	317.88 4914 5.28	1705.12 2258.07	-20.73 12667.44	9480.26 15682.87	50.88 88428.7	13629.18 17074.71	22.85 9804 1.36
POP	6320 967 (2.05e +07)	4861 (2.01e+08)	624266.1 (502023.7)	136877 (1938 290)	2.96 e+ 07 4.68e+07	81047 2.01e+08	9716993 2.08e+07	6140 1.01e+08	3708364 4269779	6729 1.95e+07	595517 949663.7	4861 7074988
FDI	105364.7 (1848356)	-8860 851 (3.88e+07)	1.55 (0.81)	-2.06 (2.87)	0.68 0.57	-0.48 2.17	597058.3 4373 530	-8860851 3.88 e + 07	1.56 0.93	-4.17 5.32	2.31 3.36	-27.72 19.36

Note: SD means standard deviation, min means minimum value, and max means maximum value.

Table 3. Correlation Analysis, Source: Authors' computation

	cpiamm	gfcf	tech	crw	opnness	gdpg2	pop1
cpiamm	1.0000						
gfcf	0.3159	1.0000					
tech	-0.0897	0.0664	1.0000				
crw	0.0282	-0.1424	-0.0114	1.0000			
opnness	0.1239	0.2251	0.2163	-0.1444	1.0000		
gdpg2	-0.1757	0.0360	0.5960	0.2091	0.1732	1.0000	
pop1	0.1669	0.2584	0.0503	-0.1732	0.8201	-0.0327	1.0000
FDI	-0.0265	-0.0573	-0.0129	0.2723	-0.0105	-0.0372	-0.0151

The analysis of table 3 indicates the presence of either a positive or negative correlation among the explanatory variables. For instance, variables such as gross fixed capital formation (investment), combustible renewables and waste, trade openness, and total population are positively correlated with the CPIA macroeconomic management rating. In contrast, ICT, GDP growth, and foreign direct investment are negatively correlated with the CPIA macroeconomic management rating. Furthermore, GDP growth is negatively correlated with population growth and foreign direct investment. Regarding ICT, it is negatively correlated with combustible renewables and waste as well as foreign direct investment, while it is positively correlated with trade openness, GDP growth, and population growth. These relationships confirm the need for a dynamic model that would consider potential issues of heteroscedasticity.

5. Discussion

Table 4 presents the results concerning the relationship between ecological footprint, greenhouse gas emissions, natural resource rents, and the CPIA macroeconomic management rating, gross fixed capital formation (GFCF), individuals using the internet (TEC), combustible renewables and waste (CRW), trade openness (TOP), and foreign direct investment (FDI). The persistence of natural resource depletion, measured by the lagged value of the natural resource depletion coefficient, has a negative effect, implying that the overexploitation of natural resources over a long period can have adverse consequences.

In contrast, the persistence of CO_2 emissions and total natural resource rents have positive and statistically significant effects, respectively, indicating a steady growth in CO_2 emissions and total natural resource rents in Asia. Negative and significant correlations with the previous year's natural resource depletion can therefore be observed everywhere except in West Asia and Southwest Asia. Thus, natural resource depletion from the previous year suggests a strong economic base that can reduce natural resource depletion in the following year. However, positive and significant correlations with the previous year's CO_2 emissions are observed throughout West Asia. Furthermore, no exceptions are noted regarding the positive correlation with natural resource rents.

These results illustrate the complexity of the interactions between the exploitation of natural resources, greenhouse gas emissions, and natural resource rents, with dynamics that vary according to regions and economic contexts.

The analysis of Table 4 shows that strengthening the CPIA macroeconomic management reduces the depletion of natural resources across Asia, except in East Asia. This means that in most Asian regions, sound macroeconomic management leads to more sustainable use of natural resources. However, in East Asia, where industrialization is advanced, the increased consumption of resources may outpace management efforts, leading to persistent overexploitation. Furthermore, more effective CPIA macroeconomic management would reduce greenhouse gas emissions in Central Asia and East Asia. These results suggest that in these regions, effective macroeconomic policies have led to more sustainable practices, such as environmental regulations. These efforts may include investments in renewable energy, thereby reducing reliance on fossil fuels. In contrast, the assessment of CPIA macroeconomic management increases greenhouse gas emissions in South Asia. This situation indicates that despite potentially positive macroeconomic management, factors such as high industrialization and dependence on fossil fuels prevail. It may also reflect a lack of infrastructure for renewable energy and insufficient environmental regulation, resulting in increased emissions.

The analysis of the results reveals that the assessment of CPIA macroeconomic management reduces natural resource rents across Asia, except in South Asia and West Asia. This indicates that in most regions of Asia, effective macroeconomic management tends to decrease reliance on natural resource rents, encouraging economic diversification. However, in South Asia and West Asia, this dependency may persist, suggesting that these regions have not yet fully integrated strategies for diversification or optimization of resource use. Sahan et al. (2024) highlight this effect in a systematic review of the literature on green human resource management (GHRM) and its impact on energy-saving behaviours and environmental performance. The authors argue that GHRM practices, such as training employees in energy conservation techniques, promoting eco-friendly behaviours at work, and integrating sustainability into corporate culture, can significantly enhance environmental performance. Their review reveals that organizations adopting GHRM practices not only reduce their ecological footprint but also benefit from long-term economic advantages. Degbedji et al. (2024), examining the role of governance in promoting green economic

Table 4. POLED OLS Regression with Driscoll-Kraay Standard Errors, source: Authors' computation

	Natural Resources Depletion (% of GNI)						CO2 emissions (kg per PPP $ of GDP)						Total natural resources rents (% of GDP)					
Var	Total	Central	East	South	South West	West	Total	Central	East	South	South West	West	Total	Central	East	South	South West	West
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
CPIA	-1.59*	-1.18**	1.491**	0.029	0.484*	-1.33**	-7.29	0.000	-0.16***	3.58	-2.41	1.21	-0.59**	-0.54***	-0.166	-0.166	0.063	0.39**
	(0.05)	(0.032)	(0.002)	(0.72)	(0.08)	(0.075)	(0.11)	0.057	(0.00)	(0.33)	(0.05)	(0.52)	(0.004)	(0.00)	(0.393)	(0.393)	(0.418)	(0.02)
GFCF	0.010***	-0.69*	0.006	0.01***	-0.06**	-0.112	-0.58*	3.026	0.01***	-2.5**	-0.63**	-0.68**	0.14**	-0.003	0.24	0.241	0.022	0.14*
	(0.000)	(0.092)	(0.802)	(0.00)	(0.021)	(0.102)	(0.08)	0.855	(0.00)	(0.01)	(0.07)	(0.01)	(0.018)	(0.96)	(0.102)	(0.102)	(0.736)	(0.09)
TEC	-0.29**	0.235	-0.013	-0.001	0.023**	-0.1***	-0.4***	0.000	0.08***	-1.9**	-0.323	-0.021	-0.04	-0.089	0.029	0.029	-0.030**	0.031
	(0.05)	(0.23)	(0.338)	(0.633)	(0.051)	(0.006)	(0.00)	0.148	(0.00)	(0.05)	(0.29)	(0.53)	(0.32)	(0.126)	(0.68)	(0.684)	(0.018)	(0.46)
CRW	0.99***	1.105***	0.464***	0.70***	0.35***	0.674	-0.45**	-0.000	0.02***	-1.42	-0.49	-0.34	0.34***	0.127***	-0.10**	-0.105**	0.095***	0.12**
	(0.00)	(0.00)	(0.000)	(0.00)	(0.00)	0.000	(0.04)	0.076	(0.00)	(0.52)	(0.23)	(0.71)	(0.000)	(0.000)	(0.009)	(0.009)	(0.000)	(0.01)
TOP	- 1.28***	-1.18***	1.28***	1.621	-1.39**	4.10	-5.8	4.71	-1.14***	6.38	8.121**	2.92**	0.90***	0.98***	6.76***	6.767***	0.987***	0.15**
	(0.000)	(0.000)	(0.00)	(0.654)	(0.03)	(0.42)	(0.16)	(0.29)	(0.00)	(0.46)	(0.04)	(0.03)	(0.000)	(0.000)	(0.002)	(0.002)	(0.001)	(0.02)
GDP	2.189***	1.39***	-0.03***	0.04***	-0.000	0.001	-0.6***	-3.52	2.01***	-0.06	-0.011**	-1.80**	-0.43***	-0.89***	-6.99***	-6.99***	-0.74***	-0.02
	(0.00)	(0.000)	(0.000)	(0.00)	0.731	(0.10)	(0.00)	(0.19)	(0.00)	(0.61)	(0.08)	(0.02)	(0.003)	(0.000)	(0.002)	(0.002)	(0.002)	(0.74)
POP	1.409***	0.78**	-0.001	-2.30**	7.12***	-0.001	2.46**	8.98***	2.04***	2.50	-3.57***	-9.76	0.081**	0.78***	-2.52**	-2.523*	0.160	0.59
	(0.00)	(0.02)	(0.000)	(0.02)	(0.00)	(0.01)	(0.04)	(0.000)	(0.00)	(0.37)	(0.008)	(0.18)	(0.024)	(0.000)	(0.019)	(0.019)	(0.460)	(0.10)
FDI	2.25*	-0.297	0.643	0.44***	0.128	-0.580	-9.58**	0.001	0.041	-8.7**	-13.45	-0.536	-0.032	0.109	-0.037	-0.037	-0.139	0.11**
	(0.00)	(0.56)	(0.464)	(0.00)	(0.90)	(0.29)	0.03)	(0.16)	0.000	(0.00)	(0.18)	(0.48)	(0.680)	(0.112)	(0.716)	(0.716)	(0.437)	(0.01)
cons	-6.43***	10.18**	85.78***	-1.26***	-1.93	2.909	8.2***	2.003**	0.001**	9.9***	8.96***	-9.29**	-9.03***	-6.03***	-9.24**	-9.24***	-9.76***	-2.35
	(0.000)	(0.029)	(0.00)	(0.00)	(0.22)	(0.012)	(0.00)	(0.001)	(0.00)	(0.00)	(0.000)	(0.010)	(0.000)	(0.000)	(0.002)	(0.002)	(0.000)	(0.66)
Prob	0.00***	0.000***	0.00***	0.000***	0.00***	0.0***	0.0***	0.04	0.00***	0.0***	0.00***	0.00***	0.00***	0.000***	0.000***	0.000***	0.00***	0.00***
R^2	0.6841	0.8949	0.9994	0.9679	0.9787	0.9923	0.4259	0.9975	0.981	0.8343	0.9925	0.8802	0.9747	0.9996	0.9929	0.9929	0.9995	0.9597

Note: *, **, and *** means significant at 1%, 5% and 10%, respectively.

growth, argue that strong institutions are necessary to foster an environment conducive to green growth, which integrates economic development and environmental sustainability.

The results from Table 4 show that individual internet usage reduces natural resource depletion across all Asian countries. This finding may be related to improved efficiency of processes through digitalization, access to environmental information, and the promotion of more sustainable practices via online platforms. For example, the internet facilitates better management of natural resources, optimizes supply chains, and encourages more environmentally friendly technological innovations. However, this effect is positive in Central Asia and East Asia. In these regions, we can say that the internet may primarily be used to support economic activities that require more natural resources, such as mining or industrial production.

In most regions of Asia, the effect of internet usage on greenhouse gas emissions is negative and significant, except in East Asia. This can be explained by the fact that digitalization reduces the need for certain physical activities, such as travel for meetings through video conferencing, or the dematerialization of some services, thereby reducing energy consumption and greenhouse gas emissions. Additionally, the internet encourages innovation in green technologies and energy efficiency. If the result is different in East Asia, it may be due to the high energy demand associated with internet usage, particularly in countries like China, where a significant portion of energy is still produced from fossil fuels. Thus, even though the internet may reduce some emissions, the increase in energy use offsets these benefits.

Regarding natural resource rents, we observe a positive effect of internet usage across all Asian countries, but a negative effect in South Asia and Southeast Asia. The first aspect of this result could indicate that the internet promotes more efficient exploitation of natural resources, thereby increasing revenues from these resources. For instance, digital technologies can improve resource exploration or enable more profitable management of natural resources. The second aspect notes that internet usage seems to have a negative effect on natural resource rents. This could signal a faster economic transition to less resource-dependent sectors, such as digital services or technology industries. This transition could reduce reliance on extractive industries and lead to a decrease in revenues from natural resource exploitation. These conclusions are similar to those obtained by Usman et al. (2024), who indicated that ICT has a positive and significant effect on environmental sustainability. Furthermore, they demonstrated that technological innovations have a positive and significant impact on sustainable development goals.

The results from Table 4 indicate that the use of combustible renewable energy and waste increases natural resource depletion across all Asian countries. Indeed, the use of combustible renewable energy and waste, such as wood or agricultural residues, tends to deplete natural resources in all Asian countries. This may seem surprising, as these sources are labelled *renewable*, but in fact, if they are used too intensively, they can deplete resources such as forests or soils. In contrast, the use of renewable energy and waste reduces greenhouse gas emissions in Central Asia and Southwest Asia while increasing greenhouse gas emissions in East Asia. In Central Asia and Southwest Asia, renewable energies (like solar and wind) and waste are used more efficiently to replace polluting energy sources like coal or oil. This leads to a decrease in GHG emissions, as these clean energies generate significantly less CO_2 when producing electricity or heat.

These countries may have stricter policies promoting renewable energies or benefit from favourable natural conditions (such as abundant sunlight or wind), facilitating the transition to cleaner energies. On the other hand, in East Asia, although renewable energies are utilized, they may coexist with fossil fuels like coal, which is still widely used for electricity production. The increase in GHG emissions could be explained by the fact that the energy production infrastructure is not fully adapted for an efficient transition to renewable energies, resulting in a mix of technologies that do not reduce emissions as effectively. Regarding natural resource rents, the use of renewable energy and waste increases natural resource rents across all Asian countries, except in East Asia and Southwest Asia.

The use of renewable energy and waste can create economic opportunities in Asia, particularly by increasing revenues generated from natural resource exploitation. For example, converting waste into an energy source can reduce waste management costs while creating a new source of income. Thus, the use of renewable energy and waste contributes to the increase in natural resource rents in most Asian countries by creating economic opportunities and promoting sustainability. However, in East Asia and Southwest Asia, factors such as reliance on fossil fuels, insufficient infrastructure, and inefficient use limit these benefits. Mohamed et al. (2024) revisit the Environmental Kuznets Curve (EKC) hypothesis, which posits that environmental degradation initially increases with economic growth but eventually decreases as countries develop and adopt cleaner technologies. The study focuses on the role of renewable energy in reducing carbon emissions and ecological footprints in electricity production. Their findings reveal that the consumption of renewable energy contributes to reducing emissions and decreasing the ecological footprint, but the impact is more significant in countries with higher income levels and better institutional quality.

Our analyses reveal that trade openness increases natural resource depletion, greenhouse gas emissions, and natural resource rents across much of Asia. Indeed, trade openness can lead to intensified exploitation of natural resources to meet the increased demand for products in the international market. Countries that open up more to trade may exploit their natural resources (such as minerals, oil, and forests) at a faster pace to satisfy this demand, contributing to their depletion.

Moreover, an increase in trade often comes with a rise in the transportation of goods, which requires fossil fuels, thereby contributing to greenhouse gas emissions. Additionally, intensified industrial activities for the production of goods for export can also lead to higher emissions, especially if the technologies employed are not environmentally friendly. While trade openness may exacerbate resource depletion and greenhouse gas emissions, it can also generate higher rents for natural resources. Countries that export natural resources can benefit from higher prices in international markets, potentially increasing revenues from the exploitation of these resources. This can create economic incentives for governments to intensify resource exploitation, even if it has negative consequences for the environment. Peters et al. (2011), examining the growth of emissions transfers via international trade from 1990 to 2008, highlight the importance of accounting for emissions based on consumption rather than production. This study shows how international trade can lead to the displacement of emissions from developed countries to developing countries, complicating efforts to reduce global carbon emissions.

The results from Table 4 indicate that GDP growth increases natural resource depletion across all Asian countries. However, this effect is negative for Central Asia and East Asia. Indeed, it is observed that GDP growth leads to greater use of natural resources throughout Asia. This may be due to increased industrialization, infrastructure expansion, and the exploitation of resources (such as minerals, oil, gas, or forests) to support economic growth. Nevertheless, unlike the trend observed across the countries, GDP growth appears to reduce natural resource depletion in the two mentioned regions. This could be explained by greater efficiency in resource use, stricter environmental policies, or a shift towards industries that are less dependent on natural resources. In East Asia, South Asia, and West Asia, GDP growth is associated with a significant reduction in greenhouse gas emissions. This phenomenon can be attributed to efforts to improve energy efficiency, the adoption of cleaner technologies, or policies encouraging companies to reduce their emissions.

We also observe that economic growth reduces natural resource rents, which are the revenues generated from the exploitation of these resources. This may indicate that economies are diversifying their income sources as they grow, becoming less dependent on natural resources for economic prosperity. However, in regions like South Asia and Southwest Asia, GDP growth increases natural resource rents, which could suggest that the economies in these areas remain heavily reliant on the exploitation of natural resources to support their growth. According to Zhang and Cheng (2009), who analyze the relationships between economic growth, energy consumption, and carbon emissions in China, they established causal links between the variables, providing insights into the dynamics of China's energy-intensive economic growth and its environmental consequences. Liu et al. (2015) propose a revised estimate of carbon emissions from fossil fuel combustion and production in China. Their work highlights the challenges associated with accurately measuring and reporting carbon emissions, especially in rapidly industrializing countries. The findings of this study have important implications for global carbon accounting and efforts to combat climate change.

Public investment negatively impacts natural resource depletion across Asia, except for South Asia and West Asia, where it is not significant. Indeed, in regions where public investment is effective, it can be directed towards sustainable development projects, promoting more responsible and sustainable use of natural resources. This includes initiatives such as resource conservation, implementing environmental regulations, and supporting sustainable technologies. However, in South Asia and West Asia, the lack of a significant effect may indicate that investments are not optimized for sustainability or are misdirected, leading to ongoing and unsustainable resource exploitation. Furthermore, investment reduces greenhouse gas emissions throughout Asia, except in Central Asia. This may suggest that investments are focused on less polluting infrastructures and technologies, such as renewable energy, public transport, and energy efficiency. However, in Central Asia, the lack of emission reduction could be due to a strong dependence on fossil fuels and a lack of infrastructure for alternative energy sources, making it difficult to transition to more sustainable practices. On the other hand, investment increases natural resource rents in Asia, except in South Asia. This result could indicate that investments contribute to increased exploitation of natural resources, which can boost short-term revenues for governments and businesses. However, in South Asia, the absence of such an increase may be attributed to structural challenges or ineffective policies that do not allow for fully capitalizing on available resources. It is also possible that South Asia faces limitations in infrastructure or exploitation capacity, which hampers the generation of rents from natural resources.

The results from Table 4 indicate that population growth increases natural resource depletion in Asian countries, except for Central Asia and West Asia, where the effect is negative. In areas where the effect is negative, this can be explained by a higher demand for resources to meet the needs of the growing population, such as energy, agricultural land, and raw materials. In regions where the opposite effect occurs—where population growth is associated with an increase in natural resource depletion—this result could be attributed to several factors specific to these areas, such as economies that are less dependent on intensive natural resource exploitation or more effi-

cient technologies in resource consumption. In Central Asia and East Asia, demographic growth leads to an increase in greenhouse gas emissions. This could be explained by increasing industrialization and urbanization in these areas, which are often accompanied by higher fossil fuel consumption and polluting industrial activities.
In contrast, demographic growth reduces greenhouse gas emissions in West Asia. This could be related to the use of cleaner technologies or stricter environmental policies, as well as an economy that is less focused on heavy industries that emit CO_2. We also observe that population growth increases natural resource rents in South Asia, Southwest Asia, and West Asia, but reduces them in East Asia. In these regions, where population growth leads to an increase in natural resource rents, this may be linked to increased exploitation of natural resources to meet rising domestic demand. Natural resource rents refer to the revenues generated from the exploitation of resources such as oil, gas, minerals, etc.
Conversely, population growth reduces natural resource rents in East Asia. This could be due to economic diversification, moving away from dependence on natural resources to focus more on other sectors like technology or services, thereby diminishing the importance of revenues derived from natural resource exploitation. This work emphasizes the importance of considering social practices and systemic factors in addressing environmental challenges, proposing a more holistic perspective on transitions toward sustainability. The United Nations' *World Population Prospects* report (2023) provides crucial demographic data and projections that have significant implications for environmental sustainability. Although the report is not exclusively focused on environmental issues, it offers essential context for understanding the long-term challenges of sustainable development in light of global population growth and demographic changes.
The results from Table 3 indicate that foreign direct investment (FDI) reduces natural resource depletion, greenhouse gas emissions, and natural resource rents. However, the effect is reversed in East Asia for natural resource depletion; in East and South Asia for greenhouse gas emissions; and in Central Asia and then South Asia for natural resource rents in most Asian countries. This can be explained by the fact that FDI generally introduces more advanced and efficient technologies, promoting a more rational use of natural resources. Additionally, foreign companies may be subject to stricter environmental standards, leading to reduced greenhouse gas emissions and more sustainable management of natural resources. These results are similar to those obtained by Dossou et al. (2023).
Indeed, they demonstrated that foreign direct investment has a positive and significant effect on environmental sustainability. It is noteworthy that the variation in results also reflects differences in environmental regulation across regions in Asia. Countries with stricter regulations may better channel FDI into ecologically sustainable sectors, while those with weaker regulations may suffer the negative effects of FDI in polluting sectors. Lau et al. (2014) study the Environmental Kuznets Curve (EKC) hypothesis in the context of Malaysia, integrating the roles of foreign direct investment (FDI) and trade. Their results support the existence of an EKC for carbon emissions in Malaysia, with FDI and trade playing significant roles in this relationship.

6. Robustness Checks

The analysis of Tables 5 and 6 indicates that the results are similar to those presented in Table 3. These results show that the macroeconomic management of the CPIA and foreign direct investments have a negative and significant effect on ecological footprint, greenhouse gas emissions, and natural resource rents. Furthermore, the results reveal that individual internet use is negatively and significantly associated with natural resource depletion and greenhouse gas emissions, suggesting that a policy aimed at increasing the number of internet users could reduce natural resource depletion and greenhouse gas emissions. Most importantly, population growth increases natural resource depletion and greenhouse gas emissions in several Asian countries.

Conclusion

This study analyzes the determinants of ecological footprints, greenhouse gas (GHG) emissions, and natural resource rents for 43 Asian countries from 1990 to 2023, emphasizing their implications for sustainable development in alignment with the United Nations Sustainable Development Goals (SDGs 7, 8, 9, 13, and 15). The study employs the Generalized Method of Moments (GMM) estimator, supported by the fixed effects model (FEM) and pooled OLS regression with Driscoll-Kraay standard errors, to provide robust empirical insights.
The findings reveal that macroeconomic management (CPIA), GDP growth, foreign direct investment (FDI), technology adoption, renewable energy consumption, waste management, investment, population growth, and trade openness significantly impact environmental sustainability, particularly in relation to natural resource depletion, GHG emissions, and natural resource rents. These factors influence sustainable development by determining the balance between economic expansion and environmental conservation.
An improvement in macroeconomic management (CPIA) reduces natural resource depletion, GHG emissions, and natural resource rents, except in South Asia and West Asia. This suggests that effective governance, economic diversification, and institutional transparency promote sustainable economic policies that reduce environmental

Table 5. Fixed Effect, Source: Authors; computation

	Natural Resources Depletion (% of GNI)						CO_2 emissions (kg per PPP $ of GDP)						Total natural resources rents (% of GDP)					
Var	Total	East	Central	South	South West	West	Total	East	Central	South	South West	West	Total	East	Central	South	South West	West
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
CPIA	-0.004 (0.963)	-0.6*** (0.00)	-0.16 (0.39)	0.06 (0.44)	0.021 (0.80)	0.301 (0.22)	-0.087 (0.45)	0.25*** (0.00)	-0.19*** (0.00)	-0.054 (0.04)	0.016 (0.41)	0.080 (0.68)	-0.004 (0.96)	-0.61** (0.05)	-0.16 (0.39)	0.06 (0.44)	0.02 (0.80)	0.30 (0.22)
GFCF	0.15*** (0.00)	0.021 (0.64)	0.24 (0.10)	0.19* (0.05)	0.03 (0.65)	0.16* (0.06)	-0.68** (0.02)	-8.55 (0.32)	0.01*** (0.00)	0.01** (0.01)	-0.01** (0.01)	-0.012 0.262	0.15*** (0.00)	0.021 0.640	0.241 (0.102)	0.19** (0.05)	0.03 (0.65)	0.16* (0.06)
TECH	-0.04** (0.02)	-0.017 (0.42)	0.02 (0.68)	0.08* (0.06)	-0.03** (0.01)	0.03 (0.44)	0.06* (0.07)	0.00** (0.02)	0.10*** (0.00)	0.002 (0.25)	0.99*** (0.00)	-0.01* (0.08)	-0.04** (0.02)	0.017 0.422	0.029 (0.68)	0.08* (0.06)	-0.03 (0.01)	0.03 (0.44)
CRW	0.11*** (0.000)	0.10*** (0.00)	-0.10*** (0.00)	-0.013 (0.76)	-0.042 (0.19)	0.11** (0.03)	0.20** (0.02)	-0.14*** (0.00)	0.97*** (0.00)	0.041 (0.22)	-0.05 (0.37)	0.009 (0. 81)	0.11*** (0.00)	0.10*** (0.001)	-0.10** (0.00)	-0.01 (0.76)	-0.04 (0.19)	0.11** (0.03)
TOP	0.143 (0.32)	0.198 (0.35)	6.76*** (0.00)	1.29*** (0.00)	-1.36 (0.46)	-0.55 (0.66)	0.41 (0.64)	4.57 (0.52)	-8.8*** (0.00)	2.73** (0.028)	2.02 (0.48)	6.55*** (0.001)	0.14 (0.32)	0.198 (0.35)	6.76*** (0.00)	1.29** (0.00)	-1.36 (0.46)	-0.55 (0.66)
GDP	0.041 0.756	-0.131 0.569	-6.99*** (0.002)	-1.396 0.000	1.71 (0.38)	0.735 0.593	-0.302 0.760	-4.031 0.204	0.001 0.000	- 0.000 0.000	-0.000 0.003	- 0.000 0.004	0.041 0.756	-0.131 (0.56)	-6.9*** (0.002)	-1.3*** (0.000)	1.71 (0.38)	0.735 (0.59)
POP	1.09*** (0.000)	0.52*** (0.007)	-2.523 (0.019)	0.334 (0.349)	0.84* (0.099)	0. 988 0.130	-2.261 0.001	1.89 0.874	-1.54 0.000	-3.11 0.002	-7.21 0.887	-5.23 0.001	1.099 0.000	0.524 0.007	-2.52 0.019	0.334 0.349	0.84* (0.09)	0.98 (0.13)
FD	0.031 0.131	0.15 (0.00)	-0.037 (0.71)	-0.005 (0.74)	-0.14 (0.44)	0.100 (0.15)	-0.188 0.004	0.001 0.080	0.434 (0.000)	-0.08** (0.02)	-0.34 (0.19)	0.009 (0.96)	0.031 (0.13)	0.15*** (0.00)	0.037 0.716	-0.005 0.742	-0.14 (0.44)	0.10 (0.15)
CONS	-8.960 (0.026)	-0.98 (0.76)	-59.2*** 0.002	-16.8*** (0.00)	20.4** (0.04)	4.01* (0.07)	8.66* (0.07)	0.82** (0.01)	0.81** (0.01)	5.14*** (0.00)	4.93** (0.03)	2.395 (0.03)	-8.96 (0.02)	-0.98 (0.76)	-5.2*** (0.00)	-16.8*** (0.00)	20.41 (0.47)	4.01 (0.78)
Prob	0.00***	0.00***	0.00***	0.00***	0.00***	0.00***	0.0***	0.00***	0.00***	0.00***	0.00***	0.00***	0.00***	0.00***	0.00***	0.00***	0.00***	0.00***
Rsq	0.75	0.82	0.99	0.89	0.98	0.95	0.53	0.58	0.90	0.84	0.90	0.66	0.75	0.82	0.92	0.89	0.98	0.95

Note: *, **, and *** means significant at 1%, 5% and 10%, respectively.

Table 6. GMM, source: Authors' computation

	Natural resources depletion (% of GNI)						CO_2 emissions (kg per PPP $ of GDP)						Total natural resources rents (% of GDP)					
Var	Total	Central	East	South	South West	West	Total	Central	East	South	South West	West	Total	Central	East	South	South West	West
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	19	18
L1.	-5.1*** (0.00)	-7.07*** (0.00)	-1.29*** (0.00)	-4.04* (0.10)	-4.04 (0.106)	1.2*** (0.00)	0.98*** (0.00)	1.91** (0.00)	0.29*** (0.00)	2.9*** (0.00)	0.16*** (0.00)	-0.82*** (0.00)	2.69*** (0.00)	3.13 (0.68)	-5.88 (0.42)	8.6*** (0.00)	6.80*** (0.00)	2.00*** (0.00)
CPIA	-8.56*** (0.00)	-1.83 (0.34)	0.149* (0.07)	-1.51* (0.07)	-1.51** (0.07)	0.586 (0.22)	0.04 (0.77)	-2.16*** (0.00)	-0.3*** (0.00)	0.67** (0.04)	0.024 (0.74)	1.327 (0.37)	-0.91*** (0.00)	-5.22*** (0.00)	-0.22* (0.09)	0.26*** (0.00)	0.009 (0.87)	1.06** (0.01)
GFCF	-1.3*** (0.00)	-7.3*** (0.00)	-0.81*** (0.00)	-1.865 (0.08)	-1.86* (0.08)	0.056 (0.66)	-0.2*** (0.00)	1.78*** (0.00)	-0.05** (0.05)	-1.9*** (0.00)	-0.40*** (0.00)	-0.52 (0.16)	0.47*** (0.00)	0.76** (0.04)	0.23*** (0.00)	-0.6*** (0.00)	0.099 (0.10)	-0.02 (0.81)
TECH	-2.13*** (0.00)	2.97*** (0.00)	0.19*** (0.00)	0.728 (0.39)	0.728 (0.39)	0.02 (0.78)	-0.06*** (0.03)	-0.70*** (0.00)	0.29*** (0.00)	- 0.1** (0.03)	-0.09*** (0.00)	-0.18 (0.34)	0.06*** (0.00)	0.03 (0.82)	0.04 (0.44)	-0.03* (0.09)	-0.04*** (0.00)	0.001 (0.95)
CRW	6.36** (0.00)	10.4*** (0.00)	1.11** (0.00)	0.86** (0.00)	0.86*** (0.00)	1.18*** (0.00)	0.04 (0.16)	-0.70*** (0.00)	0.49*** (0.00)	-0.16 (0.13)	-0.12*** (0.00)	-0.26 (0.41)	0.27*** (0.00)	-0.22 (0.24)	-0.10*** (0.00)	0.11*** (0.00)	-0.027** (0.04)	0.06*** (0.00)
TOP	-0.91 (0.10)	87.2*** (0.000)	-0.073 (0.34)	-1.696 (0.58)	-1.69 (0.58)	0.61*** (0.00)	-0.03 (0.83)	0.73*** (0.00)	0.01*** (0.00)	1.86*** (0.00)	0.22* (0.08)	3.8*** (0.00)	1.17*** (0.00)	0.76*** (0.00)	7.06*** (0.00)	0.33** (0.00)	0.23*** (0.00)	0.080 (0.59)
GDP	6.85** (0.00)	-8.7*** (0.001)	-3.4*** (0.00)	-0.049 (0.98)	-0.04 (0.98)	-0.4*** (0.00)	0.16 (0.26)	0.16 (0.26)	-0.53** (0.01)	-0.38* (0.07)	-0.09 (0.11)	-2.12*** (0.00)	-0.8*** (0.00)	-0.71*** (0.00)	-7.30*** (0.00)	0.21*** (0.00)	0.12*** (0.00)	-0.05 (0.96)
TOP	5.19*** (0.00)	-30.15** (0.04)	1.43*** (0.00)	6.495*** (0.00)	6.49*** (0.00)	-1.4*** (0.00)	0.051 (0.74)	21.6*** (0.00)	12.1*** (0.00)	1.677 0.048	-0.135 (0.35)	-6.53*** (0.00)	- 0.385 0.000	2.069 0.001	-2.36** (0.02)	0.74*** (0.00)	0.64*** (0.00)	0.66*** (0.000)
FDI	- 1.78*** (0.00)	-8.44 *** (0.000)	0.38*** (0.000)	-1.149 (0.55)	-1.149 0.550	-0.04 (0.71)	-0.31** (0.01)	-0.40*** (0.00)	0.01*** (0.00)	0.57** (0.03)	0.05 (0.32)	0.533 (0.20)	-0.11** (0.01)	2.29*** (0.00)	-0.02 (0.86)	0.16*** (0.00)	- 0.112 (0.292)	0.059 (0.423)
cons	-25.39*** (0.000)	-685.7*** (0.00)	-3.2*** (0.001)	-50.77*** (0.00)	-50.77*** (0.00)	-7.07 (0.52)	-0.11 (0.905)	-316.3*** (0.00)	3.24*** (0.00)	-27.29** (0.012)	1.762 (0.12)	9.29 (0.705)	-6.67*** (0.00)	-27.3*** (0.00)	-64.9*** (0.00)	-6.56 (0.00)	-3.91** (0.00)	-2.94 (0.24)
Wald	4858.02	234-27.43	887 7.75	15212.1	15212.	53618.7	25570.31	117.28	117.28	20616.4	18720.71	305.27	1.4	40181.81	4.23	4.48	9.51	6.005
Prob	0.000***	0.00888	0.00***	0.008**	0.00***	0.00***	0.000***	0.000***	0.00***	0.000**	0.000***	0.0000	0.00***	0.00***	0.00***	0.00***	0.00***	0.00***
AR(1)	0.61 (0.545)	-1.13 (0.258)	-0.24 0.808	-0.50 0.620	-0.50 0.620	-2.8*** (0.00)	-4.7*** (0.00)	-2.7*** (0.00)	-1.5*** (0.00)	-1.13 0.258	0.23 0.820	-2.61 0.009	-0.23 (0.81)	0.92 (0.35)	-2.2** (0.02)	0.77 (0.44)	0.46 (0.64)	-2.71*** (0.007)
AR(2)	-0.37 (0.711)	-2.09** (0.03)	-1.60 (0.10)	0.58 (0.56)	0.58 (0.56)	3.04*** (0.00)	1.76* (0.07)	0.16* (0.08)	1.26* (0.07)	0.25 0.803	-1.74 0.081	-1.19 0.233	-0.14 (0.88)	-6.28*** (0.00)	-1.08 (0.28)	-1.01 (0.31)	-1.41 (0.15)	1.43 (0.15)
Sar(1)	59.6*** (0.000)	10.97** (0.012)	16.0*** (0.000)	23.16*** (0.001)	23.16*** (0.001)	11.20** (0.04)	65.33 (0.78)	2.56 (0.61)	67.57 (0.87)	61.00 0.000	64.57 0.00	10.05 0.074	937.8*** (0.00)	15.72 (0.94)	8.03** (0.04)	4.13*** 0.000	3.02*** (0.002)	3.78* (0.06)
Sar(2)	371.22 (0.000)	10.94*** (0.00)	10.49*** (0.00)	23.16*** (0.00)	23.1*** (0.00)	11.20 (0.024)	55.59 (0.89)	23.16*** (0.00)	23.16*** (0.00)	23.16*** (0.00)	57.08*** (0.000)	10.05** (0.040)	200.2*** (0.00)	6.72 (1.00)	8.03** (0.01)	5.78*** (0.00)	43.6*** (0.00)	33.9** (0.026)
Diff	188.3*** (0.00)	0.00 (1.00)	0.00 (1.00)	0.00 (1.000)	0.00 (1.00)	0.00 1.000	9.74 0.083	0.00 (1.00)	0.00 (1.00)	0.00 (1.00)	7.48** (0.024)	-0.00 (1.000)	737.6*** (0.000)	9.00 (1.01)	0.06 (1.00)	-1.65 1.000	-0.60 1.000	-0.17*** (1.000)
Sar(3)	36.2*** (0.000)	66.2*** (0.000)	16.2*** (0.000)	23.16*** (0.000)	23.16*** (0.00)	11.20** (0.02)	14.10** (0.02)	13.21** (0.02)	13.20** (0.02)	41.20** (0.02)	11.20** (0.02)	10.05** (0.04)	665.8*** (0.000)	36.8** (0.02)	36.8** (0.02)	16.2** (0.02)	25.8** (0.02)	36.8** (0.02)
Diff	193.3*** (0.000)	0.00 (1.000)	0.00 (1.000)	0.00 (1.000)	0.00 1.000	0.00 1.000	0.00 (1.000)	0.00 (1.000)	0.00 (1.000)	0.00 (1.000)	0.00 (1.000)	0.00 1.000	271.9*** (0.000)	2.01*** (0.000)	2.0*** (0.000)	-3.0*** (.000)	-3.09*** (.000)	-3.09*** (.000)

Note: *, **, and *** means significant at 1%, 5% and 10%, respectively.

degradation, aligning with SDG 8 (Decent Work and Economic Growth) and SDG 9 (Industry, Innovation, and Infrastructure).

The results reveal that technology adoption and individual internet use are negatively associated with natural resource depletion and GHG emissions, suggesting that digital transformation and technological innovations contribute to environmental sustainability. Expanding internet accessibility and promoting digital economies may reduce environmental degradation and enhance resource efficiency, in line with SDG 9 (Industry, Innovation, and Infrastructure) and SDG 13 (Climate Action). However, in South Asia and Southeast Asia, increasing internet usage is linked to lower natural resource rents, indicating a shift toward technology-driven industries and reduced dependence on resource extraction.

The findings also indicate that foreign direct investment (FDI) significantly reduces natural resource depletion, GHG emissions, and natural resource rents, suggesting that sustainable investment inflows introduce efficient technologies and cleaner production processes. However, in East and South Asia, FDI increases GHG emissions, possibly due to industrial expansion and energy-intensive production activities. These findings highlight the importance of sustainable FDI policies that promote clean energy adoption, resource efficiency, and environmentally friendly business practices, aligning with SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action).

The results suggest that GDP growth increases natural resource depletion in most Asian economies, but in Central and East Asia, economic growth is associated with lower resource depletion due to higher efficiency in resource use, environmental policies, and the expansion of knowledge-based industries. In East Asia, South Asia, and West Asia, GDP growth reduces GHG emissions, reflecting the transition toward energy efficiency, cleaner technologies, and carbon-reduction policies. Furthermore, GDP growth is linked to a decline in natural resource rents, indicating economic diversification and reduced dependence on natural resources, which supports SDG 8 (Decent Work and Economic Growth) and SDG 9 (Industry, Innovation, and Infrastructure).

Population growth contributes to higher natural resource depletion across Asia. In Central Asia and East Asia, population expansion is linked to rising GHG emissions, whereas in West Asia, population growth is associated with lower emissions, possibly due to energy efficiency measures. These results emphasize the need for sustainable population management, resource conservation, and urban planning to mitigate the environmental consequences of demographic expansion, in line with SDG 13 (Climate Action) and SDG 15 (Life on Land).

Based on these findings, several policy recommendations are proposed to enhance sustainable development in Asia. Strengthening governance and macroeconomic management can foster renewable energy projects, economic diversification, and environmental accountability. Expanding digital access and technological innovation can contribute to resource efficiency and emission reductions, while sustainable FDI policies should integrate green investment frameworks to attract eco-friendly industrialization. Economic growth policies should promote low-carbon industries, ecological taxation, and renewable energy subsidies, ensuring a balance between economic expansion and environmental protection. Moreover, sustainable urban planning and resource management are essential to mitigate the environmental impact of population growth and ensure the long-term conservation of natural ecosystems.

This study contributes to the literature by identifying the key determinants of ecological footprints, GHG emissions, and natural resource rents, emphasizing their role in sustainable development. Given variations in governance and environmental policies across different continents, future research should extend this analysis to other regions. Additionally, country-specific studies with time-series data could provide deeper insights into individual policy effectiveness. Further research may also explore the moderating role of governance quality and FDI in shaping environmental sustainability outcomes. This study provides empirical evidence that sustainable development requires a multidimensional approach, integrating macroeconomic policies, digital transformation, green investment, economic diversification, and population management. By aligning economic strategies with SDG 7, SDG 8, SDG 9, SDG 13, and SDG 15, policymakers can foster a resilient and sustainable future for Asia.

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