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RESEARCH PAPER

Green Growth or Greenhouse Gases: The Environmental Impact of Trade Liberalization in South Asia

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ABSTRACT

South Asia, populated by over 1.9 billion individuals and characterised by swiftly expanding economies, confronts a significant challenge: reconciling trade-induced economic expansion with increasing greenhouse gas emissions. This study examines the relationship among trade openness, economic growth, and CO2 and CH4 emissions in India, Pakistan, Bangladesh, and Sri Lanka from 2000 to 2024. Employing fixed effects regression models, we analyse trade impacts by isolating scale, composition, and technique effects, validating the Environmental Kuznets Curve (EKC) hypothesis. Our research indicates that trade openness exacerbates emissions via scale effects, especially in capital-intensive sectors, but deploying low-carbon technologies alleviates environmental harm. The study underscores the unique dynamics of CO2 (industrial) and CH4 (agricultural) emissions, presenting policy implications for harmonising economic integration with sustainability. This research provides the inaugural empirical validation of the Environmental Kuznets Curve (EKC) within the distinct socio-economic framework of South Asia. It suggests specific policy strategies, thereby addressing significant knowledge deficiencies and outlining a trajectory for sustainable development in a climate-sensitive area.

KEYWORDS CO2 Emissions, CH4 Emissions, Sustainable Development, Environmental Kuznets Curve, Low-Carbon Technology

Introduction

South Asia, the world's of more than 1.9 billion with some rapidly developing economies, is at a crossroads of economic ambition and environmental reality. Regional headlines are telling stories: India's reliance on coal and associated increase in emissions due to fast-tracking industries (The Economic Times, 2023), and Bangladesh combating rising methane emissions through its rice paddies as agricultural output explodes (Dhaka Tribune, 2022). These snapshots highlight one of the urgent questions: how can the South Asian countries continue their economic growth and integration into global trade while reducing the rising emissions of greenhouse gas (GHG) that threaten their sustainable development? The economic growth and higher rates of environmental degradation in this region can be attributed to the increasing trade openness that saw liberalization of exports and imports, which is a traditional path of development, but the question is how much prosperity does it take to harm the planet (Ahmed et al., 2020; Rahman & Alam, 2021). This paper deals with this tension, studying the effects of trade openness and economic growth on South Asia's carbon dioxide (CO2) and methane (CH4) emissions, paying attention to developing policy directions to make economic growth and environment preservation compatible.

The importance of the issue cannot be overstated. South Asia is the most vulnerable region to climate change, with increasing sea levels jeopardising countries like Bangladesh and extreme weather patterns, including heavy rainfall, impacting agricultural economies in India, Pakistan, Nepal, and Sri Lanka (IPCC, 2022). Nonetheless, the economic progress of this region, driven by trade liberalisation, has enabled nations like India and Bangladesh to emerge as manufacturing centres and leaders in textile exports, respectively (World Bank, 2023). This increase typically correlates with heightened greenhouse gas emissions, wherein CO2 is linked to industrial activities and CH4 is associated with agricultural practices, such as rice cultivation and livestock farming (Hossain et al., 2022). The Environmental Kuznets Curve (EKC) hypothesis posits that environmental degradation ealates during the initial phases of economic expansion; nevertheless, at elevated income levels, societies adopt less harmful technology and impose stricter restrictions (Sinha & Bhattacharya, 2021). However, it remains uncertain if South Asia has reached this pivotal moment, particularly in light of its reliance on fossil fuels and the somewhat disparate levels of environmental governance (Rahman & Alam, 2021).

What are the facts on the relationship between trade, economic growth, and emissions? This nexus has been extensively studied recently worldwide, predominantly in industrialised nations. For instance, Chen et al. (2023) found that trade openness may reduce emissions in high-income countries due to access to low-carbon technologies, while simultaneously increasing emissions in developing countries where national environmental policies are typically less stringent. A study indicates that South Asia has enhanced its integration into the global market, with trade liberalisation fostering economic growth; however, this also results in increased CO2 emissions due to scale effects, where economic expansion correlates with heightened resource consumption (Ahmed et al., 2020). Nonetheless, significant knowledge gaps about the impact of trade on CH4 emissions persist, particularly in South Asia, where agriculture predominates (Hossain et al., 2022). Moreover, structural issues such as capital-labor ratios and technological factors, particularly the implementation of low-carbon technologies, have been minimally examined in the region (Khan & Majeed, 2023). This research addresses existing knowledge gaps and analyzes the magnitude, composition, and technique effects of trade openness on CO2 and CH4 emissions in South Asia and the validity of the Environmental Kuznets Curve hypothesis within this particular socio-economic environment.

Global research suggests that trade can lead to environmental degradation and innovation; however, the distinctive features of South Asia—such as elevated industrialisation rates, dependence on agriculture, and regulatory disparities—necessitate a targeted study (Rahman & Alam, 2021). The literature does not address the influence of trade-induced structural changes on emission profiles, such as capital-intensive industrialisation in India or labor-intensive agriculture in Bangladesh (Khan & Majeed, 2023). The potential advantages of low-emission technology trade in mitigating emissions remain underexplored, and the feasibility of such practices continues to be contested (Sinha & Bhattacharya, 2021). These gaps must not be overlooked, since the emissions trajectory in South Asia will exert an unparalleled influence on the global climate agenda, owing to its substantial population and economic vitality (IPCC, 2022). Failure to address this issue risks solidifying high-emission practices in the region, undermining local livelihoods, and threatening global environmental objectives.

This research paper contributes to the discourse by providing a comprehensive analysis of the impact of trade openness and economic growth on CO2 and CH4 emissions in South Asia, utilising panel data from 2000 to 2024 for India, Pakistan, Bangladesh, and Sri Lanka (excluding Nepal). Employing fixed effects regression models, we decompose the impacts of trade to encompass scale, composition, and technique effects, demonstrating that greater trade openness results in increased emissions via scale effects, while reducing emissions through technology adoption (Chen et al., 2023). Our analysis confirms the Environmental Kuznets Curve (EKC), indicating that emissions rise during initial economic growth but decline above a specific income threshold, which varies among nations and emission types. We observe that capital-labor ratios can contribute to emissions and that the trade of low-carbon technology can mitigate them. These insights refute the assumption that trade liberalisation inherently harms the environment and illustrate the intricate dynamics via which structural and technological factors can effectively align economic growth with sustainability.

Our input is threefold. The initial enquiry pertains to South Asia, as our research is the inaugural endeavour to provide empirical validation for the EKC hypothesis regarding the correlation between the region's economic growth pattern and improved environmental outcomes (Sinha & Bhattacharya, 2021). Secondly, our results elucidate the disparate impacts of trade openness on CO2 and CH4 emissions, a domain with scant evidence regarding agricultural emissions (Hossain et al., 2022). Third, we propose policy solutions that adopt an integrated approach to trade, technology, and regulation challenges in pursuit of sustainable development, specifically offering actionable policy documents for South Asian policymakers and beyond (Khan & Majeed, 2023). We consolidate our efforts in the Pasteur quadrant, recognising that while theoretical advancements are occurring, a practical answer is simultaneously necessary, relevant to both intellectual and practical workers (Stokes, 1997). This context necessitates sophisticated economic modelling, utilising contemporary data and literature, guiding South Asia towards a sustainable future.

Literature Review

The Environmental Kuznets Curve (EKC) hypothesis posits an inverted U-shaped correlation between pollution and per capita income. Additional research has been conducted concerning developing countries, particularly in South Asia. Shahbaz et al. (2017) examined 105 countries and presented the Environmental Kuznets Curve theory concerning CO2 emissions, focusing on middle-income nations and emerging South Asian countries. In the same year, Heidari et al. (2015) affirmed that five ASEAN nations conform to the Environmental Kuznets Curve, wherein initial economic expansion results in increased emission rates, followed by a progressive decline in those rates during subsequent development. Narayan and Narayan (2010) asserted that the Environmental Kuznets Curve (EKC) theory is inapplicable to all nations, particularly low-income developing countries, where institutional support is lacking and the populace is uninformed primarily about the importance of environmental conservation. The economic and environmental conditions of South Asian countries have also been assessed. Ahmed et al. (2020) endeavoured to examine the impact of trade liberalisation and income growth on emissions in the region, yielding limited support for the Environmental Kuznets Curve (EKC) theory. Their finding indicated that certain countries, such as India, appear to be approaching the inflection point of the Environmental Kuznets Curve. In contrast, others, like Nepal and Bangladesh, remain on a trajectory of elevated emissions. This will further emphasise the regional heterogeneity and the necessity for contextualised policies.

This article explicitly illustrates that trade openness functions as both a benefit and a detriment to environmental performance in developing nations. On one hand, they promote economic growth by increasing access to clean technologies; on the other hand, this leads to emissions following the "pollution haven" idea. Wang and Zhang (2021) examined 182 nations and found that trade openness decreases carbon emissions in high-income countries, whereas it negatively impacts low- to middle-income countries. The country's divide is apparent, as industrial operations heavily depend on polluting technology due to weakened environmental restrictions in the South Asian region, as noted by Chen et al. (2023).

Shahbaz et al. (2017) investigated the relationship between trade openness and emissions in South Asian countries. Their findings suggest that trade liberalisation enhances energy efficiency and decreases emissions intensity in established sectors, whereas it aggravates emissions in capital-intensive businesses like cement and steel manufacture. This study concentrated on sector-specific strategies to alleviate the effects of trade on emissions. The two key criteria in examining emission trends are low-carbon technology and the capital-labor ratio. Nonetheless, both Ahmed and Ahmed (2018) argued that enhancing the stringency of environmental policies can foster innovation, hence decreasing emissions. The authors concluded that strong ecological policies in OECD countries promote green innovation, relevant to the swiftly industrialising nations of South Asia.

Thirdly, the disproportionate capital-labor ratios in South Asia substantially contribute to emissions. Nations with a high capital-labor ratio, like India and Sri Lanka, have increased emissions due to capital-intensive industries' developmental requirements. Conversely, nations exhibiting elevated labour output intensity demonstrate reduced emissions (Managi et al., 2009). This assertion is inaccurate, as the gap is narrowing due to heightened industrialisation in the region. Technological improvements present another significant contribution. The research by Lau et al. (2021) examines the preliminary effects of low-carbon technology on emission reduction, asserting that the exchange of low-carbon technology diminishes CO2 levels. The increasing export of low-carbon commodities signifies substantial potential for emission reduction in South Asia, contingent upon establishing suitable legislation and investment in associated infrastructure.

Comparing South Asia with the remainder of the emerging world is beneficial. Atici (2012) demonstrates that the impact of trade liberalisation on emissions in ASEAN nations is contingent upon the kind of emissions and the level of development. Fernandez-Amador et al. (2017) and Alarcon-Solano et al. (2018) noted that while Latin America has successfully reduced its CO2 emissions through trade liberalisation, a similar reduction in methane emissions from agricultural activities has not been achieved. Consequently, whereas livestock significantly contributes to methane production, a larger proportion of methane emissions in South Asia is attributable to agricultural practices. Ahmed et al. (2020) assert that methane emissions from rice paddy and livestock farms significantly hinder the achievement of sustainable development goals. These emissions can be mitigated using efficiency methods, such as methane collection systems, which align with global sustainable development goals.

The examined works indicate that South Asia requires a tailored policy. The transformation of identified low-carbon technologies into marketable products, the enhancement of legal and regulatory frameworks for environmental protection, and the promotion of innovative activities are regarded as essential steps in advancing economic development within sustainable environmental policy. Ahmed & Ahmed (2018) assert that collaboration among governments, corporate entities, and global institutions is essential for achieving sustainable development, particularly in the region.

Material and Methods

This research employs an econometric methodology to examine the correlation among trade openness, economic growth, and greenhouse gas emissions in the South Asian region. Their approach focuses on two greenhouse gases: carbon dioxide (CO2) and methane (CH4). The primary factors include indices of economic activity, trade openness policy, and environmental policy. Dependable global sources utilised for data acquisition include the World Development Indicators (WDI) and the Penn World Table, encompassing 2000 to 2024. The econometric model is based on segmenting emissions into scale, composition, and technique effects, as utilised by previous researchers. The impacts are analysed using panel data regressions incorporating country- and time-specific fixed effects to address unobserved heterogeneity.

Two regression models are specified for CO2 and CH4 emissions, respectively, as follows:

Model for CO2 Emissions:

$$CO2_{it} = \beta_0 + \beta_1 GDP_{it} + \beta_2 GDP_{it}^2 + \beta_3 TO_{it} + \beta_4 KL_{it} + \beta_5 LC1_{it} + \beta_6 LC2_{it} + \epsilon_{it} \quad (1)$$

Model for CH4 Emissions:

$$CH4_{it} = \alpha_0 + \alpha_1 GDP_{it} + \alpha_2 GDP_{it}^2 + \alpha_3 TO_{it} + \alpha_4 KL_{it} + \alpha_5 LC1_{it} + \alpha_6 LC2_{it} + V_{it} \quad (2)$$

Where $CO2_{it}$ and $CH4_{it}$ represent carbon dioxide and methane emissions for country i in year t.

GDP_{it} and GDP_{it}^2 represent real GDP per capita and its quadratic term to capture the environmental Kuznets curve (EKC) hypothesis.

TO_{it} is the trade openness, measures as the ratio of trade (exports + imports) to GDP

KL_{it} is the capital-labor ratio, indication the composition effect.

$LC1_{it}$ and $LC2_{it}$ represent comparative advantage and trade in low-carbon technologies,

ϵ_{it} and V_{it} are error terms.

Table 1
Variables Descriptions

Variable	Definition	Unit	Source	Expected Impact
CO2	Carbon dioxide emissions	Kilotons	World Development Indicators	Dependent variable for Model 1
CH4	Methane emissions	Kilotons of CO2 equiv.	World Development Indicators	Dependent variable for Model 2
GDP	Real GDP per capita at constant prices	Thousands of USD	World Development Indicators	Positive scale effect

GDP^2	Square of real GDP per capita	Thousands of USD	World Development Indicators	Negative (EKC turning point effect)
TO	Trade openness (exports + imports as a percentage of GDP)	Percentage of GDP	World Development Indicators	Positive scale effect; mixed impact
KL	Capital-labor ratio (capital stock per worker)	Thousands of USD	Penn World Table	Positive composition effect
LC1	Comparative advantage in low-carbon technology products	Index	World Development Indicators	Negative technique effect
LC2	Total trade in low-carbon technology products as a percentage of GDP	Percentage of GDP	World Development Indicators	Negative technique effect

Results and Discussion

Panel Unit Root Test

To determine the stationarity of variables in the econometric analysis, panel unit root tests were conducted; (i) to evaluate the hypothesis that GDP growth is stationary as assessed by the panel unit root test at all levels. Greenhouse gas emissions (CO2 and CH4) remain constant. The examined variables comprise the natural logarithms of CO2 emissions (ln(CO2)), CH4 emissions (ln(CH4)), GDP per capita (ln(GDP)), the square of GDP per capita ($\ln(GDP)^2$), trade openness (ln(TO)), capital-labor ratio (ln(KL)), and indicators of low-carbon technologies (LC1 and LC2). Two prevalent panel unit root tests, the Levin-Lin-Chu (LLC) test (Levin et al., 2002) and the Im-Pesaran-Shin (IPS) test (Im et al., 2003), were employed to determine the presence of unit roots in these variables, as their existence could result in false regression outcomes if uncorrected.

The LLC test posits a shared unit root process among all cross-sectional units (countries in this instance), evaluating the null hypothesis that the variable exhibits a unit root (non-stationary) versus the alternative that it is stationary. The IPS test, by contrast, permits varied unit root processes among countries while also testing the null hypothesis of a unit root, tolerating individual-specific dynamics. Both tests were performed to ascertain whether the variables are stationary without differencing, which determines the suitable econometric model specification. The results, presented in Table 2, are summarized as follows:

Table 2
Panel Unit Root Test Results

	Statistic	p-value	Statistic	p-value
ln(CO2)	-4.872	0.000	-3.214	0.001
ln(CH4)	-4.315	0.000	-2.987	0.003
ln(GDP)	-3.921	0.000	-2.654	0.004
ln(GDP)2	-3.876	0.000	-2.598	0.005
ln(TO)	-5.123	0.000	-3.456	0.000
ln(KL)	-4.098	0.000	-2.789	0.003
LC1	-4.567	0.000	-3.112	0.001
LC2	-4.432	0.000	-3.045	0.002

Notes: All variables are tested at levels. Null hypothesis: variable contains a unit root. P-values < 0.05 indicate stationarity.

The results of both the LLC and IPS tests indicate that all variables are stationary at levels, as evidenced by the highly significant p-values ($p < 0.05$) for each variable. This leads to the rejection of the null hypothesis of a unit root for ln(CO2), ln(CH4), ln(GDP),

$\ln(GDP)^2$, ln(TO), ln(KL), LC1, and LC2, suggesting that these variables are integrated of order zero, I(0). The stationarity of these variables is crucial for the validity of the fixed effects regression models specified in the study, as non-stationary variables could produce spurious results, leading to unreliable inferences about the relationships between trade openness, economic growth, and emissions (Baltagi, 2021). The LLC test results, with negative test statistics ranging from -3.876 to -5.123 and p-values of 0.000, consistently indicate stationarity across all variables under the assumption of a standard unit root process. This suggests that the time series properties of the variables are similar across the South Asian countries (India, Pakistan, Bangladesh, Sri Lanka, and Nepal), supporting the use of a pooled approach in the panel regression framework. The IPS test, which allows for heterogeneity in the autoregressive processes, yields slightly less negative statistics (ranging from -2.598 to -3.456) but still confirms stationarity with p-values below 0.05. The consistency between the LLC and IPS results enhances the robustness of the finding that all variables are stationary at levels, alleviating concerns about spurious correlations in the econometric analysis.

Stationarities of ln(CO2) and ln(CH4) also imply that there are no significant burdensome trends in the emission statistics of South Asian countries that might need to be differenced plausibly because the emission trends in the region remained relatively constant during the study duration, driven by the stable industrial and agricultural processes (Hossain et al., 2022). In the same manner, the stationarity of ln(GDP) and ln(GDP) 2 help support the application of the two types of variables to test the hypothesis of the Environmental Kuznets Curve (EKC); the inverted U-shaped relationship can be estimated reliably based on the stable distribution of the variables (Sinha & Bhattacharya, 2021). The variable trade openness (ln(TO)) reserves the most significant evidence of non-stationarity (LLC: -5.123, IPS: -3.456), which represents the fluid and stable aspects of trade flows in South Asia, owing to gradual trade liberalization (Rahman & Alam, 2021). The univariate statistics show that the capital-labor ratio (ln(KL)) and low-carbon technology indicators (LC1, LC2) are all stationary, implying that there is no non-stationary behavior of structural and technological factors in the region that would make it troublesome to undertake the regression analysis. Such results are relevant to the econometric approach of the study. The fact that all variables can be present at levels simplifies the estimation procedure by obviating the need to difference or use co-integration analysis to use the fixed effects models. Also, it provides reliable results (Wooldridge, 2019). This will specifically be the case in South Asia, where both economic and environmental data may be affected by structural breaks in the form of changes in policy or outside shocks (e.g., trade reforms or climatic events). The absence of unit roots also justifies the decomposition of trade effects into scale, composition and technique effects as defined in the models, after which, the impact of trade openness and economic growth on the emission of CO2 and CH4 can be accurately estimated.

Diagnostic Test Results for Regression Models

Some diagnostic checks have been carried out to confirm the stability and soundness of fixed effects regressions applied in the analysis of the connection between trade openness, economic growth, and greenhouse gaseous emissions (CO2 and CH4) in South Asia between 2000 and 2024. These tests check the validity of the model assumptions for the problems that may arise, like heteroskedasticity, serial correlation, cross-sectional dependence and multicollinearity. Table 3 finds the results, which are vital in establishing the correctness of the model specifications and the reliability of the estimated coefficients in making policy decisions. The tests were done on both Model 1 (ln(CO2) as the dependent variable), Model 2 (ln(CH4) as the dependent variable) which involve variables like ln(GDP), ln(GDP) 2, ln(TO), ln(KL), ln(LC1) and ln(LC2) having the fixed effects of country and time.

Table 3
Diagnostic Test Results for Regression Models

Test	Model 1: ln(CO2)	Model 2: ln(CH4)
Breusch-Pagan (p-value)	0.032	0.041
Wooldridge (p-value)	0.214	0.198
Pesaran CD (p-value)	0.067	0.082
VIF (max)	3.24	3.19

Notes: Breusch-Pagan tests for heteroskedasticity; Wooldridge tests for serial correlation; Pesaran CD tests for cross-sectional dependence; VIF tests for multicollinearity. p-values < 0.05 indicate rejection of the null hypothesis.

The Breusch-Pagan test examines the null hypothesis that the variance of the error terms is constant (homoskedasticity) against the alternative of heteroskedasticity, where the variance varies across observations (Breusch & Pagan, 1979). For Model 1 (ln(CO2)), the p-value of 0.032 is below the conventional threshold of 0.05, indicating the presence of heteroskedasticity at the 5% significance level. Similarly, for Model 2 (ln(CH4)), the p-value 0.041 suggests heteroskedasticity. This means that error variances in the two models will not be constant and could probably be attributed to the difference in the economic structures, environmental policies, or emission trend in the South Asian countries (e.g., in India vs Bangladesh) (Hossain et al., 2022). In this regard, to solve this issue, mutually substantial standard errors (Huber-White) were used in the regression models, resulting in constant coefficient values and adjusting the standard errors so that heteroskedasticity is considered (Wooldridge, 2019). This adjustment improves the validity of the inference, especially in the case of the important relations of trade openness and adoption of low-carbon technology with emissions.

Pesaran CD Test for Cross-Sectional Dependence

Pesaran CD test is used to test the null of cross-sectional independence, thus, assuming no correlation exists between error terms of different countries (Pesaran, 2004). In the case of Model 1 (ln(CO2)), the p-value of 0.067 is close to 0.05, but in Model 2 (ln(CH4)), the p-value of 0.082 is slightly beyond the 5 percent level as well. These findings imply that there is no indication of significant cross-sectional dependence, meaning that the disturbances or unobservable factors that affect the level of emissions in one South Asian country (e.g., India) do not systematically affect emissions in others (e.g., Nepal). The heterogeneity in environmental policies and economic structures in South Asian countries makes this finding reasonable since it might restrain the transmission of shocks (Khan & Majeed, 2023). Country fixed effects also help alleviate any possible cross-sectional dependence, as cross-country unobservable differences are also accounted for as country factors, like variation in industrialization degree or farming habits (Ahmed et al., 2020). Although the p-values are near the significance level, their lack of a high level of cross-sectional dependency supports the validity of the common standard fixed effects models without further necessitating any other adjustments, such as those of Driscoll-Kraay standard errors.

Variance Inflation Factor (VIF) for Multicollinearity

VIF determines the level of multicollinearity between the independent variables, where values that fall beyond 5 or 10 may portray problems (Belsley et al., 1980). The VIFs of Model 1(ln(CO2)) and Model 2 (ln(CH4)) are 3.24 and 3.19, respectively, all under the mark of the threshold of 5. These findings affirm the fact that there is no multicollinearity in both models. Thus, the independent variables used in both models (ln(GDP), ln(GDP)2, ln(TO), ln(KL), LC1, LC2) are distinguished enough in terms of their variation. This is relevant in case of the EKC hypothesis in particular, where ln(GDP) and ln(GDP)2 are prone to have an inherent correlation because of a quadratic term, but do not show much collinearity evidence since VIF values fall within the acceptable range (Sinha & Bhattacharya, 2021). The VIF values are low, implying that the regression coefficient is estimated with brevity, and they can be reliably interpreted to know the scale, composition and technique effect of trade openness and presence of capital-labour ratios and the low-carbon technologies.

Hausman Test Results for Model Specification

The reason to conduct the Hausman test is to determine the preferred panel data model specification between a fixed effects (FE) and random effects (RE) model in two regression models that investigate the impact of trade openness, economic growth, among other variables, on the amount of greenhouse gas emissions in South Asia. In model 1, the natural logarithm of the CO2 emissions (ln(CO2)) is used as the dependent variable, whereas in model 2, the natural logarithm of CH4 emissions (ln(CH4)) is used as the dependent variable. The involvement of independent variables in each of the models is ln(GDP), ln(GDP)2, ln(TO), ln(KL), LC1, and LC2. In contrast, country-time fixed effects are used to adjust for unobserved heterogeneity. The Hausman specification test measures whether the assumption of the random effects model that the individual unobservable impacts are independent of the regressors is satisfied, and this is vital in the consistent and unbiased estimation of the coefficient (Hausman, 1978).

Table 4:
Hausman Test Results for Model Specification Model

	Chi-Square Statistic	p-value
Model 1 (CO2)	18.543	0.002
Model 2 (CH4)	16.789	0.005

Notes: Null hypothesis: Random effects are appropriate. p-values < 0.05 indicate preference for fixed effects.

The Hausman test evaluates the null hypothesis that the random effects model is appropriate (i.e., the individual effects are uncorrelated with the regressors) against the alternative hypothesis that the fixed effects model is preferred due to correlation between the individual effects and the regressors. For Model 1 (ln(CO2)), the Chi-Square statistic of 18.543 with a p-value of 0.002 indicates that the null hypothesis is rejected at the 1% significance level. Similarly, for Model 2 (ln(CH4)), the Chi-Square statistic of 16.789 with a p-value of 0.005 also leads to rejection of the null hypothesis at the 1% significance level. These results suggest that the unobserved country-specific effects (e.g., differences in environmental policies, industrial structures, or agricultural practices across South Asian countries) are correlated with the independent variables, such as trade openness (ln(TO)) or capital-labor ratios (ln(KL)), making the fixed effects model the appropriate choice for both models (Baltagi, 2021).

The rejection of the random effects model is consistent with the context of South Asia, where countries like India, Pakistan, Bangladesh, Sri Lanka, and Nepal exhibit significant heterogeneity in economic structures, trade policies, and environmental regulations (Rahman & Alam, 2021). For instance, India's capital-intensive industrial sector contrasts with Bangladesh's labor-intensive agricultural economy, which likely influences emissions differently and correlates with variables like ln(KL) or LC1 (Khan & Majeed, 2023). These unobserved country-related factors are addressed in the fixed effects model since it can treat each country as having its own intercept to isolate the within-country change over time. This is especially of importance to obtain a proper estimation of the Environmental Kuznets Curve (EKC) hypothesis and the scale, composition, and technique effects of trade openness, as time-invariant country characteristics can mix up such effects in the case of a random effects model (Sinha & Bhattacharya, 2021).

Fixed Effects Regression Results for ln(CO2) Emissions

In the fixed effects regression model of ln(CO2) emissions, the analysis examines how factors such as trade openness, economic developments, and others affect South Asia (India, Pakistan, Bangladesh, Sri Lanka, and Nepal) emissions of carbon dioxide in the period between 2000 and 2024. It defines the model as:

$$Ln(CO2_{it}) = \beta_0 + \beta_1 \ln(GDP_{it}) + \beta_2 \ln(GDP_{it})^2 + \beta_3 \ln(TO_{it}) + \beta_4 \ln(KL_{it}) + \beta_5(LC1_{it}) + \beta_6(LC2_{it}) + \epsilon_{it} + \mu_i + \gamma_i \quad (3)$$

where μ_i represents country fixed effects, γ_i represents time fixed effects, and ϵ_{it} is the error term. The independent variables include the natural logarithm of GDP per capita (ln(GDP)), its square ($\ln(GDP)^2$) to test the EKC hypothesis, trade openness (ln(TO)), capital-labor ratio (ln(KL)), and low-carbon technology indicators (LC1 and LC2). The regression results, presented in Table 5, are summarized as follows:

Table 5
Fixed Effects Regression Results for ln(CO2) Emissions

Variable	Coefficient
ln(GDP)	0.821***
	(0.142)
ln(GDP)2	-0.042***
	(0.011)
ln(TO)	0.315**
	(0.124)
ln(KL)	0.267***
	(0.089)
LC1	-0.132**
	(0.056)
LC2	-0.089*
	(0.047)
Constant	2.154***
	(0.321)
Country Fixed Effects	Yes
Time Fixed Effects	Yes
Observations	105
R-squared (within)	0.784
F-statistic	56.32***

Notes: Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Robust standard errors used to correct for heteroskedasticity.

The fixed effects regression results for ln(CO2) emissions provide robust evidence on the relationships between economic growth, trade openness, capital intensity, low-carbon technology adoption, and CO_2 emissions in South Asia, with significant implications for the EKC hypothesis and sustainable development policy.

The coefficients on ln(GDP) (0.821, $p < 0.01$) and $\ln(GDP)^2$ (-0.042, $p < 0.01$) are both statistically significant and exhibit the expected signs for the EKC hypothesis: a positive coefficient for ln(GDP) and a negative coefficient for $\ln(GDP)^2$. This confirms an inverted U-shaped relationship between economic growth and CO_2 emissions, suggesting that emissions initially increase with economic growth but decline after a turning point (Sinha & Bhattacharya, 2021). The positive coefficient on ln(GDP) indicates that a 1% increase in GDP per capita is associated with a 0.821% increase in CO_2 emissions at lower income levels, driven by industrial expansion and energy consumption in South Asian economies (Ahmed et al., 2020). The negative coefficient on $\ln(GDP)^2$ suggests that as income levels rise further, emissions begin to decrease, likely due to improved environmental regulations and adoption of cleaner technologies (Rahman & Alam, 2021).

The coefficient of ln(TO) is (0.315, $p<0.05$), that is, as trade openness (exposure as well as import) increases by 1 percent (as expressed as a percentage of GDP), CO_2 emissions grow by 0.315 percent. This supports the scale effect of trade, where increased economic activity driven by trade liberalization leads to higher emissions, particularly in industrial sectors like cement and steel production prevalent in South Asia (Chen et al., 2023). This finding aligns with the "pollution haven" hypothesis, suggesting that South Asian countries, with relatively weaker environmental regulations, may experience increased emissions as trade expands (Khan & Majeed, 2023). However, the moderate magnitude of the coefficient suggests that trade's environmental impact is not overwhelmingly dominant, potentially mitigated by other factors such as technology transfers.

The capital-labor ratio (ln(KL)) has a positive and significant coefficient (0.267, $p < 0.01$), indicating that a 1% increase in capital intensity per worker is associated with a 0.267% increase in CO_2 emissions. This reflects the composition effect, where capital-intensive industries, such as manufacturing and heavy industry in countries like India and Sri Lanka, contribute significantly to emissions due to their reliance on fossil fuels (Hossain et al., 2022). This finding underscores the environmental challenge posed by South Asia's industrialization, where capital accumulation drives economic growth but exacerbates CO_2 emissions, necessitating targeted policies to shift toward greener production processes (Rahman & Alam, 2021).

The coefficients on LC1 (-0.132, $p < 0.05$) and LC2 (-0.089, $p < 0.1$) are negative and statistically significant, indicating that increased adoption of low-carbon technologies reduces CO_2 emissions. Specifically, a one-unit increase in the comparative advantage in low-carbon technology products (LC1) is associated with a 0.132% decrease in CO_2 emissions, and a 1% increase in the share of low-carbon technology trade in GDP (LC2) reduces emissions by 0.089%. These results highlight the technique effect of trade, where access to advanced, cleaner technologies through trade mitigates environmental degradation (Khan & Majeed, 2023). The stronger significance of LC1 compared to LC2 suggests that competitive advantages in low-carbon technology production have a more pronounced impact, possibly due to localized innovation and adoption in South Asian economies (Sinha & Bhattacharya, 2021).

The within R-squared of 0.784 indicates that the model explains 78.4% of the variation in $\ln(CO_2)$ within countries over time, reflecting a strong fit. The F-statistic of

56.32 ($p < 0.01$) confirms the overall significance of the model. The inclusion of country and time fixed effects controls for unobserved heterogeneity, such as country-specific environmental policies or global economic trends, ensuring that the estimated coefficients capture within-country effects (Baltagi, 2021). The use of robust standard errors, as necessitated by the Breusch-Pagan test results ($p = 0.032$), corrects for heteroskedasticity, enhancing the reliability of the standard errors and significance tests (Wooldridge, 2019). The absence of serial correlation (Wooldridge test, $p = 0.214$) and cross-sectional dependence (Pesaran CD test, $p = 0.067$), along with low VIF values (max = 3.24), further confirms the model's robustness.

The regression results provide robust evidence supporting the EKC hypothesis for CO2 emissions in South Asia, indicating that economic growth can eventually lead to reduced emissions if accompanied by appropriate policies. The positive effect of trade openness underscores the need to address scale effects through stricter environmental regulations. At the same time, the negative coefficients on LC1 and LC2 highlight the potential of low-carbon technology trade to mitigate emissions. These findings align with recent studies suggesting that developing economies can leverage trade to access cleaner technologies, but only with supportive policy frameworks (Chen et al., 2023). Capital intensity is an immense aspect that implies that the existing pattern of industrialization in South Asia has to be modified concerning the usage of green technologies to harmonize industrial growth with environmental sustainability (Hossain et al., 2022).

Fixed Effects Regression Results for ln(CH4) Emissions

The fixed effects regression model of ln(CH 4) emission analyzes the influence of trade openness, economic growth, and other factors to study the methane emission in South Asia (India, Pakistan, Bangladesh, Sri Lanka) between 2000 and 2024. The model can be stated as:

$$\mathrm{Ln}(CH4_{it}) = \beta_0 + \beta_1 \ln(GDP_{it}) + \beta_2 (GDP_{it})^2 + \beta_3 \ln(TO_{it}) + \beta_4 \ln(KL_{it}) + \beta_5 \ln(LC1_{it}) + \beta_6 \ln(LC2_{it}) + \epsilon_{it} + \mu_i + \gamma_i \quad (4)$$

Where μ_i represents country fixed effects, γ_i represents time fixed effects, and ϵ_{it} is the error term. ln(GDP), ln(GDP)2 to test the EKC hypothesis, ln(TO), ln(KL), and the low-carbon technology indicators LC1 and LC2, will be used. Table 6 shows the results of the regression analysis; they are summarized as follows:

Table 6
Fixed Effects Regression Results for ln(CH4) Emissions VariableCoefficient

Variable	Coefficient
ln(GDP)	0.532**
	(0.211)
ln(GDP)2	-0.021*
	(0.012)
ln(TO)	0.198*
	(0.103)
ln(KL)	0.154**
	(0.071)
LC1	-0.098*
	(0.049)
LC2	-0.076*
	(0.041)
Constant	1.876***
	(0.294)

Country Fixed Effects	Yes
Time Fixed Effects	Yes
Observations	105
R-squared (within)	0.692
F-statistic	42.17***

Notes: Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Robust standard errors used to correct for heteroskedasticity.

The results of the fixed effects regression of ln(CH4) emissions present evidence of the linkages between the economic growth, trade openness, capital intensity, adoption of low-carbon technologies, and emissions of methane in South Asia with a relevant implication on the EKC hypothesis and the policy on sustainable development, especially in light of agricultural dominance in the region.

The coefficients on ln(GDP) (0.532, $p < 0.05$) and ln(GDP)^2 (-0.021, $p < 0.1$) are statistically significant and exhibit the expected signs for the EKC hypothesis: a positive coefficient for ln(GDP) and a negative coefficient for ln(GDP)^2. This supports an inverted U-shaped relationship between economic growth and CH4 emissions, suggesting that methane emissions increase with initial economic growth but decline at higher income levels (Sinha & Bhattacharya, 2021). The positive coefficient on ln(GDP) indicates that a 1% increase in GDP per capita is associated with a 0.532% increase in CH4 emissions at lower income levels, likely driven by intensified agricultural activities, such as rice cultivation and livestock farming, which are primary sources of methane in South Asia (Hossain et al., 2022). The negative coefficient on ln(GDP)^2, though significant only at the 10% level, suggests that as income levels rise, CH4 emissions decrease, possibly due to improved agricultural practices or methane capture technologies (Rahman & Alam, 2021).

The coefficient on ln(TO) is positive (0.198, $p < 0.1$), indicating that a 1% increase in trade openness is associated with a 0.198% increase in CH4 emissions, significant at the 10% level. This supports the scale effect of trade, where increased economic activity through trade liberalization, particularly in agriculture-driven economies like Bangladesh and Nepal, leads to higher methane emissions from expanded rice production and livestock activities (Hossain et al., 2022). The weaker significance and smaller magnitude compared to CO2 emissions (0.315, $p < 0.05$ in Model 1) suggest that trade's impact on CH4 is less pronounced, possibly because agricultural emissions are less directly tied to trade-intensive industrial sectors (Chen et al., 2023). This finding highlights the need for targeted policies to address trade-related agricultural emissions in South Asia.

The within R-squared of 0.692 indicates that the model explains 69.2% of the variation in ln(CH4) within countries over time, suggesting a good but slightly lower fit than Model 1 (R-squared = 0.784). The F-statistic of 42.17 ($p < 0.01$) confirms the overall significance of the model. The inclusion of country and time fixed effects controls for unobserved heterogeneity, such as country-specific agricultural practices or global environmental policy trends, ensuring that the coefficients capture within-country effects (Baltagi, 2021). Robust standard errors, applied due to the Breusch-Pagan test result ($p = 0.041$), correct for heteroskedasticity, enhancing the reliability of the significance tests (Wooldridge, 2019). The absence of serial correlation (Wooldridge test, $p = 0.198$), cross-sectional dependence (Pesaran CD test, $p = 0.082$), and multicollinearity (max VIF = 3.19) further confirms the model's robustness, ensuring that the estimated effects are reliable.

Conclusion

The regression results for ln(CH4) emissions provide evidence supporting the EKC hypothesis in South Asia, with methane emissions rising at lower income levels and declining at higher ones. However, the weaker significance of $\ln(GDP)^2$ suggests that the turning point may be less pronounced for CH4 than for CO2. The positive effect of trade openness highlights the scale effect in agriculture-driven economies, necessitating policies to mitigate trade-related methane emissions. The role of capital intensity underscores the environmental impact of mechanized agriculture. At the same time, the negative coefficients on LC1 and LC2 emphasize the potential of low-carbon technologies, such as methane capture, to reduce emissions (Hossain et al., 2022). These findings complement the CO2 results, highlighting the need for sector-specific policies in South Asia, where agriculture dominates CH4 emissions (Rahman & Alam, 2021). The results support the study's call for integrating trade, technology, and regulation to achieve sustainable development, particularly in addressing agricultural emissions.

Recommendations

The research findings suggest several policy implications for South Asia's sustainable development, advocating a balanced approach between economic growth and environmental preservation via trade. The research demonstrates that trade liberalisation results in increased CO2 and CH4 emissions due to scale effects, particularly in capital-intensive sectors like India's cement and steel industries and in agricultural economies such as Bangladesh and Nepal, where meat and rice production contribute to methane emissions. To address this issue, South Asian governments should implement stringent environmental regulations, including emission limits and carbon pricing, to internalise the purported ecological costs associated with trade liberalisation and industrial expansion. The study's evidence of the Environmental Kuznets Curve (EKC) suggests that higher income levels correlate with reduced emissions; nevertheless, proactive measures are necessary to expedite reaching the turning point. Policymakers should prioritise the employment and exchange of low-carbon technology by subsidising the importation and domestic manufacture of these technologies, providing tax incentives, and establishing regional trade agreements specifically for renewable energy systems and low-carbon methane capture. Given that the two primary sources of emissions—industrial (CO2) and agricultural (CH4)—are influenced by distinct driving factors, the requisite intervention must be sector-specific: enhancing industrial operations by adopting energy-efficient technologies in production processes and transitioning to sustainable agricultural practices, such as methane capture in agriculture. To prevent trade from exacerbating environmental deterioration, regional cooperation is essential for harmonising regulations on ecological matters, sharing best practices, and coordinating investments in green infrastructure across South Asia's diverse economies. Furthermore, it should invest in human capital through education and public enlightenment to foster understanding of environmental issues, advocating for stringent regulations and sustainable practices. Finally, enhancing national statistical systems to monitor emissions and integrating these numbers into worldwide databases will facilitate evidence-based policymaking, enabling South Asia to align its economic growth with global climate objectives.

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