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Assessing the Impact of Technological Innovations and Trade Openness on Environmental Sustainability: An Empirical Study of South Asian Economies Using Panel ARDL Approach

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Abstract

This study examines the major factors that influence environmental sustainability over a 20-year period (2000–2020) in the four South Asian economies. In this study, two methods of estimation including the Pool Mean Group (PMG) estimator and the panel autoregressive distributed lag (ARDL) approach are used. The findings explore that trade openness, energy consumption, and economic expansion have a long-term positive and considerable impact on environmental deterioration, conversely technical innovation has a long-term negative impact on the environment. In short run scenario, trade openness and energy usage have significant and favourable effects on environmental degradation, whereas the economic growth and technological advancement have had a substantial negative influence on the environment. From this study, the policy makers provide the direction to the government by incentivizing technology, enforcing energy-efficient laws, promoting renewable energy, aligning trade policies with environmental goals, and enhancing regional cooperation. In order to improve South Asian environmental sustainable policies, future research should examine energy-trade-growth-technology by employing advanced techniques, and prioritizing innovation.

Keywords: Technological Innovation, Trade Openness, Environmental Sustainability, Economic growth and South Asian Economies

1. Introduction

Environmental degradation persisted as a pressing issue through both the Millennium Development Goals (2000-2015) and the Sustainable Development Goals (2015-2030) set by the UN. It is an emerging worldwide policy agenda to address climate change concerns and CO_2 emissions that are the most significant contributor to global warming, accounting for 58 percent of all greenhouse gases including Carbon Dioxide, Sulphur Hexafluoride, Methane, and Nitrous Oxide (Usman & Hammar, 2021). This is mostly due to the world's high level of energy consumption and its strong relationship with economic expansion, which allows for increased discharge of GHGs in the atmosphere (Harrathi & Almohaimeed, 2022; Usman et al., 2023). As a result, the focal point of the discussions on climate change is to promote effective initiatives in order to restrict the emission of GHGs (Kinley et al., 2021). From the last two or three decades, the efforts are made to create environmental sustainability to overcome the adverse effects on human health, ecosystems, and economic activity (Hashmi et al., 2022; Shahid et al., 2024).

In global context, 75 percent of South Asia's CO2 emissions come from India, the sixth-largest emitter in the world (Adeel et al., 2018) and South Asian economies—Bangladesh, Sri Lanka, India, Pakistan, Bhutan, Maldives, Nepal, and Afghanistan—are the major influencers at international level due to their massive populations and international trade, however, their persistent pursuit of economic growth causes a significant rise in environmental degradation (Ashiq et al., 2023; Sadia Bint Raza et al., 2024). This challenge is more crucial to maintain balance between ecological sustainability and development in these nations. For the sake of economic expansion by improving living standards, the consumption of energy rises from fossil fuels, which adds carbon emissions and exacerbates climate change.

Recently, technological advancement and trade openness are also crucial catalysts that drive nations to seek economic progress while also ensuring environmental sustainability (Jiang & Liu, 2023). Additionally, it promotes energy-saving products along with renewable energy usage, which has a favourable effects on the ecosystem (Kiani et al., 2023). Also, increased energy consumption and economic activity are two ways that trade openness reduces carbon emissions (Chen et al., 2021). Conversely, the expansion in trade and production raises carbon dioxide emissions that enables technology transfer to reduce emissions in the long term, and supports the shift from agrarian to a service-based eco-friendly economy in South Asia (Adeleye et al., 2023; Shen et al., 2024).

The prior studies explored that latest technology has the ability to reduce GHG degradation as it improves the efficiency of the energy for attaining economic development. Moreover, the environmental technology may create dual effects on GHG emissions: they affect the price of carbon-based fuels by imposing tax that reduce energy consumption and emissions of environmental pollutants, and they encourage businesses to purchase or create new technology for alternative fuels that emit fewer carbon emissions (Maqsood1 et al., 2023; Roussel et al., 2024). However, it is claimed that the rebound effect of technological advancements leads to resource depletion and environmental damage and technology used in the industrial sector often enhance production activities, which necessitate for more energy and raw materials and degrades environmental quality (Khan et al., 2017). Additionally, (Huang et al., 2021; Saeed et al., 2024; Ullah & Ali, 2024) found that trade liberalization, energy consumption, and economic growth are more significant contributors to CO_2 emissions than FDI and technological advancement, and that there is a long-term, bi-directional association between trade openness, energy use, and innovation.

The environmental degradation portrayed in this chart has displayed a consistent upward trend until 2018, highlighting its significance within the economies of South Asia. Extensive literature emphasizes the region's challenging environmental conditions, energy usage patterns, economic growth dynamics, and involvement in trade-focused economic alliances. Previous studies often relied on a single proxy to measure environmental sustainability (Ashiq et al., 2023; Zubair et al., 2024; Tawari, 2024; Rehman & Ahmad, 2024; Audi et al., 2024) However, what distinguishes this study is its innovative approach: employing multiple proxies to construct an index for technological innovation within the transportation sector (Shahid et al., 2023; Farhadi & Zaho, 2024).

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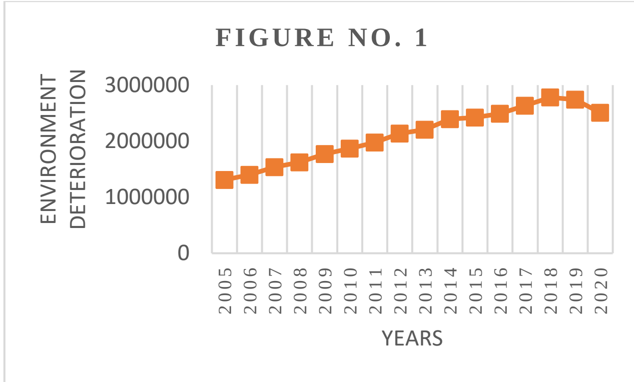

Source: Designing figure by authors with WDI dataset

1.1. Hypothesis

Following hypothesis has been used in this study:
H1: The environmental sustainability is negatively affected by technological innovation of South Asian nations.
H2: Trade openness creates a favourable impact on environmental sustainability of South Asian countries.
H3: Higher the energy consumption can create lower South Asian nations' environmental sustainability.
H4: High level of Economic growth causes low level of environmental sustainability in South Asian economies.

1.2. Objectives

The following objectives are highlighted below:

- To explore the major contributing factors of Environmental sustainability
- To formulate the policy that shall be helpful to boost up economic growth with better environment quality
- To enlist the main contributors of CO_2 emission in short and long run

This paper is organized in five chapters; the second chapter consists of literature review, third chapter is based on data collection and methodology, chapter fourth presents the analysis and discussion and last chapter provides conclusion, recommendations & policy implication.

2. Literature Review

Among global challenges, the environmental sustainability is a main concern mentioned in the United Nations' Sustainable Development Goals. Consequently, the most of the research studies highlight the determinants of environment degradation to control higher CO_2 emissions.

The extensive debate among researchers on trade and environmental quality has been discussed in the previous studies and it has significant importance in the context of trade policies. For this, Le et al. (2016) and (Azhar & Marimuthu, 2012) revealed a long run association among trade openness, economic growth, and carbon emissions, suggesting that trade typically rises environmental degradation, while the effects differ by country. Additionally, Ertugrul et al. (2016) found cointegration relationships in certain top ten CO_2-emitting less developed economies, their study revealed that trade openness and energy consumption are the key factors of carbon emissions when analyzing their impact on real income. Therefore, the research work of Mahrinasari et al. (2019) highlighted that the trade expansion created more environmental degradation in Asian countries owing to the favourable relationship between trade openness and carbon emissions, while other research studies demonstrated the negative impact of trade on carbon emissions. Moreover, the study of Xu (2019) confirmed that trade rises CO_2 in the China when they employed the generalized method of moments and ARDL to examine the effect of trade on CO_2 emissions (Minhas et al., 2024). In order to improve accuracy, these studies also included other macroeconomic variables in their research of the association among energy, income, CO_2 emissions, urbanization, trade, and population density. Conversely, international trade reduces CO_2 emissions, which enhances environmental performance (Saud et al., 2019; Song et al., 2024).

In the opinion of Du et al. (2017), environmental innovation can reduce the pollutants by improving environmental performance and the economical ways can be introduced to promote efficient usage of the energy by decreasing carbon dioxide emissions (Hodson et al. 2018). For the sake of reduction of carbon emissions, innovations play a vital role in shifting the economy toward sustainable energy sources (Álvarez-Herránz et al. 2017). In the study of Többelmann and Wendler (2020), GMM model and patent applications as innovation proxies were used to examine the impact on carbon emissions from 1992 to 2014 in EU-27 nations. According to the findings, the role of innovation was not meaningful to decrease CO_2 emissions, it had little effect on lowering carbon emissions overall. Furthermore, they proposed that the effects of increasing economic activity may outweigh the potential influence of innovation and the effect of innovation was different in various nations and areas, specially, less developed nations showing higher degrees of variability. Cansino Muñoz-Repiso et al. (2019) investigated how quality institutions and technical advancements affect the environment, noting that income and GHG emissions follow the conventional Environmental Kuznets Curve theory. They conclude that foreign direct investment and international trade have a detrimental effect on the environment, technical advancement and high-quality institutions favourably contribute to environmental sustainability.

Osobajo et al. (2020) examined the fixed effect and OLS models from 1994 to 2013 to analyze the effect of energy consumption and GDP on carbon emissions and a unidirectional association was observed between energy consumption and CO_2 emissions, they also found a bidirectional causal association between these variables and carbon emissions. Moreover, both the fixed-effect and OLS models displayed that rising energy costs and GDP are associated with higher carbon emissions. Zhou et al. (2018) tested EKC hypothesis by investigating the impact of energy consumption and economic growth on global carbon emissions and their panel quantile regression study showed that independent factors had varying effects on CO_2 emissions at different quantiles (Huang et al.,

2024). Finally, they observed that the panel's CO_2 emissions increased due to energy usage, and it affected greater on rich countries than developing ones. In South Asian nations, Kousar et al. (2020) conducted their research on the relationship among the renewable energy consumption, water shortage, environmental quality, and governance and their findings showed that water availability and renewable energy sources are the sources to decrease carbon emissions, while FDI raises carbon emissions. Furthermore, they highlighted that the effective governance may be reduced the environmental damage (Sehrish Arshad et al., 2024).
Similar to this, Zafar et al. (2020) conducted a study the effect of FDI, renewable energy, and natural resources on carbon emissions in a number of OECD nations. In their research, they discovered that plentiful natural resources and FDI follow higher CO_2 emissions, renewable energy has a favourable effect on environmental quality. Similarly, panel ARDL and dynamic fixed-effect estimators were used by Shaari et al. (2020) to study the effect of energy usage on CO_2 emissions in OIC nations (Minhas et al., 2024). According to their findings, national output has no appreciable short-term impact on carbon emissions but long-term contributions to environmental damage. Furthermore, they found that although population had no influence on carbon emissions over the long run, but it has a lower effect in the short-term. Mert et al.'s (2019) study of carbon emissions, energy consumption, and foreign direct investment in European nations supported EKC theory in their sample and noticed that energy consumption reduces the rate of CO_2 emissions, supporting the Pollution Haven Hypothesis (PHH) and finding that laws have no effect on its validity (Abro et al., 2024).
At the end, we explore the different factors of environmental sustainability including FDI, population, energy consumption, economic growth, technological innovation, trade, and urbanization from previous studies by reviewing the literature. In the light of results of previous studies on environmental sustainability of South Asian countries are not satisfactory from 2005 to 2018. Therefore, we introduce the technological innovation using different proxies to get the better results of CO_2 emission from the transport sector of South Asia.

3. Data and Methodology

In this study, we use secondary data which have been taken from World Bank database i.e. World Development Indicator of the variables including environmental sustainability, trade openness, technological innovation, FDI, energy consumption , and economic growth. All these variables are defined in table 1.

Table 1: Variable Description

Variable	Symbol	Proxy	Variable Type	Source
Environmental Sustainability	ES	CO2 emissions (kt)	Dependent Variable	WDI
Technological Innovations	TI	Patent applications, residents and non-residents	independent Variable	WDI
Trade Openness	TOP	Trade (% of GDP)	independent Variable	WDI
Energy	EN	Renewable energy consumption (% of total energy consumption)	Control Variable	WDI
Economic Growth	EG	GDP growth (annual %)	Control Variable	WDI

Note: Creating variable description table by authors

In this study, we examine the impact of technological innovation and trade openness on environmental sustainability in the South Asian economies from the time period of 2000-2022. The panel data of South Asian countries, including Bangladesh, India, Pakistan and Sri Lanka have been derived from WDI whereas the data of remaining four south economies like Afghanistan, Nepal, Bhutan and the Maldives is not completely available. The functional form of this model is given below:

$$ES = f\,(TI, TOP, EG, EN) \text{ ------------------------------------- } (1)$$

In the above-mentioned model, all variables are converted in log form to remove the heterogeneity and the specific econometric regression line is highlighted below:

$$\ln ES_{it} = \beta_{it} + \beta_1 \ln TI_{it} + \beta_2 \ln TOP_{it} + \beta_3 \ln EG_{it} + \beta_4 \ln EN_{it} + \epsilon_{it} \text{ -------------------- } (2)$$

In this study, we use patent applications from residents and non-residents for measuring technological innovations and convert it one variable through Principal Component Analysis (PCA). Then, we apply various econometric techniques to investigate the association among trade openness, technological innovation and environment sustainability. Firstly, cross-sectional dependency test is carried out to examine the effect of shocks. Second, the cross-sectionally augmented Dickey–Fuller panel unit root test of Pesaran (2007) is applied to check the stationary in the variables. Thirdly, Pedroni (1999, 2004) and Kao (1999) for cointegration tests are used to assess the equilibrium connection. Lastly, both short and long run relationships are used to test the panel pooled mean group estimator.

4. Analysis and Discussion

4.1. Descriptive Analysis

During this analysis, we check the normality of variables through Jarque-Bera test and it depends on the values of kurtosis and skewness. For the normality test, we compare the p-value and selected significance threshold, if the p-value is greater than 0.05; the variables are normal.
A careful examination of table 2 reveals an interesting trend: most variables have a positively skewed distribution, clearly departing from the theoretical norm of zero skewness. Therefore, only one variable like environmental sustainability stands out as normal except all other variables.

Table 2: Descriptive Statistics

	lnES	lnTOP	lnEN	lnEG	lnTI
Mean	2.981	10.492	8.364	0.324	11.605
Median	2.549	10.498	8.236	0.416	11.241
Max	3.951	11.056	9.578	0.697	14.096
Min	1.285	10.220	7.651	-0.371	9.619
SD	0.037	0.151	0.339	0.124	1.351
Skewness	0.138	0.652	0.568	-1.554	0.474
Kurtosis	2.914	2.778	2.152	5.599	1.837
Jarque-Bera	9.008	15.102	18.715	147.016	20.504
Probability	0.379	0.006	0.006	0.000	0.005

Note: Authors created this table by Eview 10

4.2. Panel Unit Root

Before going into the intricacies of econometric analysis, it is imperative to meticulously ascertain the variable order, since this is a prerequisite for employing any intricate analytical technique. Our study closely examined each variable for the presence of unit roots, adhering strictly to this essential principle. This review not only provides a solid basis for further econometric methods, but it also demonstrates our dedication to maintaining the accuracy and dependability of our analysis. Therefore, we employed the Im, Pesaran, and Shin (IPS) test and the Levin, Lin, and Chu (LLC) test, two well-known panel unit root tests, to achieve this. For further verification, we also used the W-Stat, Breitung, Fisher ADF, and PP tests.

Table: 3 Panel Unit Root Results

Variables		LLC	Breitung	IPS	ADF	PP	Level of Integration
lnES	At Level	-0.3144	1.6227	0.6134	12. 292	14.2011	1(1)
	Significance	0.322	0.9624	0.7037	0.5236	0.2145	
	At 1^{st} difference	-1.6925	-5.8243	-4. 8588	45.174	58.986	
	Significance	0.0353	0.002	0.0001	0.0000	0.0000	
	At Level	-2.0279	0.5650	-1.6568	22.667	16.234	1(1)
	Significance	0.0128	0.7014	0.0465	0.0965	0.2463	
	At 1^{st} difference	-4.3889	-3.2626	-3.6355	44. 341	52.412	
	Significance	0.0000	0.0005	0.0001	0.0001	0.0000	
lnEN	At Level	0.8910	4.8978	3.0572	4.0465	12.0543	1(1)
	Significance	0.6207	1.0000	0.9752	0.9842	0.6682	
	At 1^{st} difference	-2.7134	-5.9458	-6.8231	65.7089	78.148	
	Significance	0.0025	0.0013	0.0004	0.0001	0.0000	
lnEG	At Level	-6.8908	1.4335	-6.0251	12.4540	87.685	1(1)
	Significance	0.0003	0.9304	0.0000	0.0000	0.0000	
	At 1^{st} difference	-4.4776	-4.4325	-6.2697	62.4463	75.986	
	Significance	0.00011	0.0000	0.0000	0.0000	0.0000	
lnTI	At Level	0.6027	3.2491	1.1203	10.6893	8.8354	1(1)
	Significance	0.7267	0.9784	0.8644	0.7127	0.6997	
	At 1^{st} difference	-1.3473	-1.1235	-2.3283	26.964	57.8255	
	Significance	0.0754	0.0272	0.0089	0.0157	0.0000	

Note: The results of LLC and IPS, Bretuing, Fisher ADF and PP represents all the variables are stationary at 1^{st} difference.

The list of various variables used in the study is defined in table 3, and the first row displays the findings of unit root tests for different unit root techniques. Every variable had a stationary outcome at the first difference. Based on a number of prior research, it is plausible that the model variables are stable at the first difference following panel cointegration analysis (Pesaran, Shin, & Smith, 2001).

4.3. Co-Integration Results

Two panel co-integration tests of Pedroni (1999, 2004) and Kao (1999) are used in order to investigate the long-term relationship between environmental sustainability, technological innovation, trade openness, economic growth and energy consumption. Additionally, these tests are based on the Engle-Granger approach and can manage the complexity of these kinds of datasets. Multiple cross-sectional units observed throughout time are included in panel data, therefore approaches that take into consideration both possible cross-sectional interdependence across units and heterogeneous relationships are required. These tests take into account correlations between observations of different units and allow for different cointegration patterns across units, in contrast to typical cointegration tests that assume uniform connections across all units and independence of observations.

Table 4: Pedroni Test

Test	Individual Intercept and Trend	
	Penal A: between-dimension	
	Statistic	Statistic
v-statistic	-0.352	-0.352
rho-statistic	0.571	0.571
PP-statistic	-1.816***	-1.816***
ADF-statistic	-2.075**	-2.075**
	Penal B: between-dimension	
Test	Individual Intercept and Trend Statistic	
Group rho-Statistics	1.549	
Group PP-Statistics	-1.067	
Group ADF-Statistics	-1.301***	

Note: For the selection of lag length, we use Schwarz info criteria in which the values highlight with *, **, *** indicated the 1%, 5% and 10% level of significance respectively.

Table 5: Kao Test

Kao test (Engle-Granger based)	
ADF	Residual variance
-1.5211**	0.0689

Note: For the choosing of lag length, we use Schwarz info criteria in which the values highlight with *, **, *** indicated the 1%, 5% and 10% level of significance respectively.

Table 5 presents the data, which indicate that there is a consistent link between the factors. The investigation may now move forward with estimating the parameters of the dynamic error-correction model using the PMG approach because both panel cointegration tests reject the null hypothesis.

4.4. PMG Estimation Result

Panel data analysis uses the Pool Mean Group (PMG) estimator, which combines advantages of group-specific and pooled estimators. In order to increase efficiency, it pools information and permits heterogeneous coefficients between units. When cross-sectional units show distinct long-run connections across variables, tolerating varying economic actions among entities, PMG is very helpful. The panel data analysis method known as ARDL (Autoregressive Distributed Lag) takes into account both the long-term associations and the short-term dynamics of the variables. With panel data settings, where observations are connected across time and units, ARDL is very helpful in providing reliable estimates of associations that could differ between entities.

In empirical research in the fields of economics, finance, and social sciences, this technique improves statistical power and accuracy in parameter estimation, making it appropriate for examining dynamics such as economic development, convergence, and policy impacts across numerous units across time.

Table 6 Panel ARDL Results of Long Run and Short Run

Variable	Coefficient	Prob.
	Long Run	
lnTOP	2.6481	0.0197**
lnEN	2.7492	0.0000*
lnEG	3.9054	0.0001*
lnTI	-2.3322	0.0000*
C	-176.5421	0.0000*
	Short Run	
ECT	-0.1592	0.1858
d(lnTOP)	1.9664	0.0948***
d(lnEN)	0.9775	0.0027**
d(lnEN (-1))	-2.0382	0.0811***
d(lnEG)	-1.3212	0.0001*
d(lnTI)	-0.356	0.2361

Note: *, **, and *** denote 1%, 5% and 10% significance level respectively.

From long-term data analysis shown in Table 6, there is a significant 3.9% rise in CO2 emissions with a 1% shift in economic growth, and a corresponding 1.32% drop in short-term emissions. Notably, Al-Mulali's (2012) conclusions are supported by the positive and strong long-run link between economic growth and CO2 emissions. Additionally, the analysis of trade openness shows that a 1% shift causes CO2 emissions to rise 2.6% over the long term and 1.96% over the short term. This reinforces the results of Aslam et al. (2021) that trade openness and CO2 emissions have a consistent, positive, and robust connection. Furthermore, a 1%

increase in technical innovation results in an impressive 2.3% long-term reduction in CO_2 emissions and a tiny but significant 0.36% short-term reduction. These results also support the inverse link between technological innovation and CO_2 emissions, as did Lin and Zhu (2019) and Mensah et al. (2018). At the end, the energy consumption influences the significant effects on environment in short and long time period.

In table 6, the Error Correction Term value of -0.1592 indicates that any divergence from equilibrium is corrected at a rapid rate of 15.9%. This finding suggests that the identified parameters have a significant and immediate impact on reestablishing environmental balance, indicating possible significant long-term consequences on environmental contamination. The behavior of the ECT coefficient strongly affects our computations, highlighting its importance in capturing the system dynamics.

5. Conclusion, Recommendations & Policy Implications

5.1. Conclusion

The aim of this study is to investigate the factors that affect the environmental sustainability in a panel of four South Asian nations, covering a 20-year dataset from 2000 to 2020. The estimation strategies are employed including the panel autoregressive distributed lag method and Pool Mean Group estimator. Furthermore, cointegration tests, cross-sectional dependency tests, and other relevant diagnostic evaluations are used to investigate the effects. The observed findings confirm that the variables under study exhibit cointegration. In the long run, energy consumption, trade openness, and economic growth show positive and significant impacts on environmental degradation in these countries, while technological innovation is found to be negatively associated with long-term environmental sustainability. In addition, energy consumption and trade openness have positive and significant short-term effects on environmental deterioration. It is interesting, therefore, that over this time, technological progress and economic expansion have had a substantial detrimental impact on the environment.

5.2. Future Recommendations

Future research should delve deeper into the intricate relationships among energy consumption, trade openness, economic growth, and technological innovation to develop more comprehensive strategies for enhancing environmental sustainability in South Asian countries. Expanding the scope of the study to include more countries and a longer timeframe could provide a broader perspective on regional trends. Additionally, employing advanced econometric techniques and exploring potential nonlinear relationships between variables might yield more nuanced insights. Policymakers should prioritize fostering technological innovation and improving energy efficiency to mitigate the adverse environmental impacts of economic and trade activities. Finally, examining the role of policy interventions and international cooperation could offer valuable recommendations for achieving long-term environmental sustainability in the region.

5.3. Policy Implications

Based on the findings of this study, several policy implications can be drawn to enhance environmental sustainability in South Asian countries. Governments should invest in and incentivize technological advancements that enhance energy efficiency and reduce environmental impact. Implementing policies that encourage energy conservation and the use of renewable energy sources is crucial, along with regulations mandating energy-efficient practices in industries and households. Trade policies should align with environmental objectives, promoting the exchange of environmentally friendly goods and services. Sustainable economic growth should integrate environmental considerations into planning and development strategies. Robust environmental regulations and standards must be enforced, with regular monitoring and stricter penalties for non-compliance. Regional cooperation among South Asian countries can amplify the effectiveness of these policies through collaborative efforts in sharing best practices and technology transfer. Comprehensive environmental impact assessments should precede new projects or policies to identify and mitigate potential negative effects. Public engagement and education on the importance of environmental sustainability are also essential to garner widespread support and participation in sustainable practices. By adopting these measures, South Asian countries can better manage the trade-offs between economic growth and environmental health, ensuring a sustainable future.

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