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Industrialisation and Environmental Degradation in Asia: Rethinking Growth through an Ecological Lens

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This study examines the ecological impacts of industrial expansion in Asia, focusing on four key pollution dimensions: nonrenewable energy use, industrial wastewater, waste gas, and solid waste. It argues that ecological resources are exploited as unpaid inputs, representing a disinvestment in social overhead capital. While prior research often focuses on a single type of pollution, this study introduces a comprehensive Industrial Pollution Index to reflect the multidimensional nature of industrial pollution in selected Asian economies. Empirical findings suggest that industrial solid waste, wastewater, and waste gas collectively contribute significantly to environmental degradation, particularly in high-polluting countries like China and India. Conversely, lower-polluting nations exhibit cleaner industrial practices and stronger environmental regulations. The study reveals that industrialization's ecological effects vary across Asia due to differences in energy use, industrial structures, and policy effectiveness. It calls for integrated environmental governance, targeted ecological taxation, and robust regulatory frameworks to address Asia's growing ecological challenges.

JEL Classification: H5, O1, Q5, R1
Keywords: Environmental Economics, Environmental Externalities, Industrial Pollution Index, Regional Disparities, Sustainable Industrialisation

1. INTRODUCTION

The last two decades have witnessed the fastest growth in the history of Asian economies. However, this expansion might be at the expense of significant environmental degradation, leading to substantial environmental challenges like those faced by other industrialised nations during their economic development. Climate change is attributed to the Industrial Revolution, which began in 1750. In 2019, atmospheric CO2 concentrations reached 409.8 ppm (parts per million), marking the highest level in at least 800,000 years. This demonstrates that greenhouse gas (GHG) concentrations are significantly higher than they were at the onset of the industrial era (Lindsey & Dahlman, 2020). Industrialisation has a profound impact on carbon emissions in the Asia-Pacific region (Zafar, et al. 2021). Many Asian countries have quickly promoted domestic industry and attracted foreign investment without a robust plan for sustainable growth. However, the impact of industrialisation on environmental degradation varies across different regions of Asia. The Asian Development Bank (ADB) (ADB, 2001) reports that 13 of the 15 cities with the worst air pollution—and 41 of the most polluted cities globally—are in Asia.

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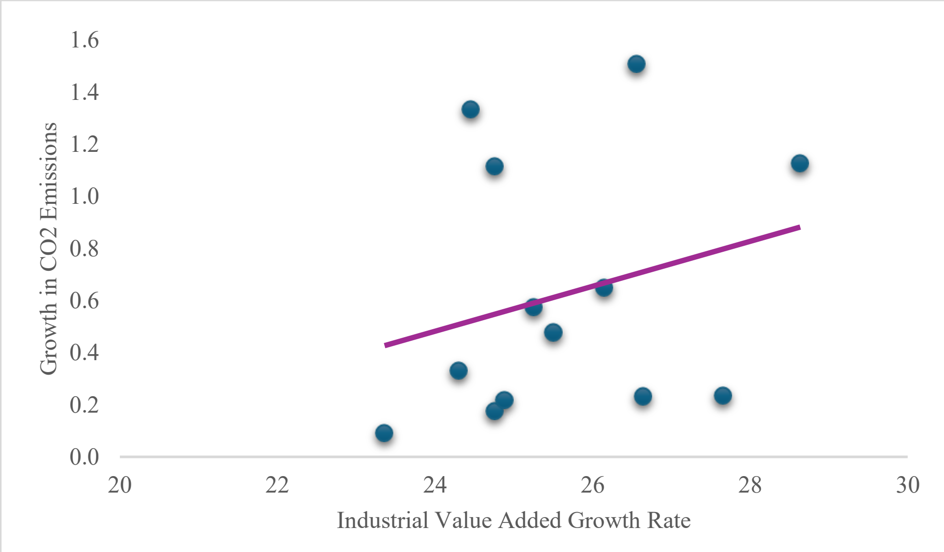
Many developing economies in Asia are grappling with increasing environmental challenges stemming from their rapid economic growth, a trend encapsulated by the Kuznets curve. This curve suggests that while economic growth initially leads to a greater environmental burden, it begins to decrease once a certain level of economic development is reached. However, many environmental issues in Asia stem from a "pollute now, clean up later" mentality, making it difficult to achieve that crucial threshold of development. Examples of these environmental challenges include sandstorms, acid rain, severe water pollution, deforestation, significant soil erosion, floods, siltation, solid waste pollution, and accidents at dumpsites. As a result, many low-income economies in Asia have not yet reached this turning point on the Kuznets curve, indicating a regression due to ongoing ecological exploitation (Chiu & Yong, 2004; Li, et al. 2018). Numerous environmental failures have arisen from industrial accidents that remain unaddressed. Despite the growing body of research highlighting how industrialisation contributes to environmental degradation and climate change, ecological challenges continue to emerge.

Since industrial pollution is a multidimensional phenomenon, however, empirical studies have focused on individual sources of industrial pollution, limiting the implications of these findings. According to UNIDO's 2019 research, energy consumption is identified as the primary driver of industrial development, which is also intensifying emissions. The industrial sector is responsible for over one-third of the world's consumption of non-renewable energy resources and emission intensity. Tsui, et al. (2025) noted that marine pollution in the Asian region stems from industrial wastewater, which contains hazardous chemicals, organic compounds, and heavy metals. The rapid growth of industry is inflicting harm on both fauna and flora due to air and water pollution. Empirical literature has shown that the main contributors to air, soil, and water degradation include the use of non-renewable energy, mismanagement of industrial solid waste, wastewater pollution, and greenhouse gas (GHG) emissions tied to industrialisation. Considering these issues, there is an urgent need to develop innovative, sustainable methodologies for assessing the negative externalities of industrialisation. A thorough identification and measurement of all dimensions of industrial pollution is crucial for effective environmental management, evaluating negative industrial externalities, and fostering ecological preservation.

We believe that the atmosphere, water, and other ecological resources may be seen as parts of social overhead capital (Uzawa, 2003), which have a positive association with industrial growth. Industrial pollution may be considered a disinvestment or a decline in this social capital and a source of growth in industrial production. Our theoretical analysis is based on the "pollution as input" approach of Baumol & Oates (1988), treating pollution or emissions not merely as residuals, but effectively as a scarce economic input or factor of production. The concept of "pollution as an input" is operationalised in this study through the Comprehensive Industrial Pollution Index (IPI), which quantifies pollution-generating activities as essential by-products—or implicit inputs—of the production process. Each component of the IPI (nonrenewable energy consumption, industrial wastewater, industrial waste gases, and industrial solid waste) represents a measurable channel through which industrial activities contribute to output while simultaneously exerting environmental pressure. Thus, the IPI components explicitly capture the productive yet degradative role of pollution within industrial systems, aligning with the "pollution as input" framework. We used industrial pollutants as a proxy for ecological resource consumption in industrial production, which increases industrial growth in selected Asian countries, as illustrated by Fig. 1.

Fig. 1. Association between CO2 and Industrial Value Added (Authors' construct



Our main argument is that ecological resources are being exploited as unpaid resources in production. Without proper compensation, ecological degradation will continue to occur as the environment is treated as an unpaid factor of production. This situation will ultimately jeopardise the sustainability of the growth process itself. Sustainability is often conceptualised through two distinct dimensions: weak sustainability and strong sustainability. Weak sustainability emphasises that natural and human-made capital can be considered largely substitutable, implying that environmental degradation can be offset by technological progress or economic growth (Gutés, 1996). In contrast, strong sustainability argues that natural capital is irreplaceable and must be preserved to maintain ecological balance and intergenerational equity (Ayres, et al. 2001). Considering these dimensions in analysing the role of natural resources in industrial growth provides a theoretical foundation for examining the trade-offs and synergies between industrial growth and environmental protection. To optimise the use of ecological resources for industrial growth, accurate measurement of all industrial pollutants is indeed necessary. And if this source is not estimated and included in the natural accounting framework, the productivity of ecological use will be incorrectly measured, ultimately leading to unsustainable industrial development.

Empirical research examining the relationship between industrialisation and climate degradation has generally concentrated on specific aspects of industrial pollution, such as CO2 emissions (Elfaki & Heriqbaldi, 2023), wastewater production (Razman, et al. 2023), solid waste accumulation (Shah, et al. 2023), and the use of non-renewable energy (Fahim, et al. 2023). Given that industrial pollution is a multifaceted issue, no study has comprehensively measured and analysed the overall impact of industrial pollution—including all its dimensions—on industrial productivity in any region. To fill this research gap and provide a more holistic evaluation, this paper contributes in several significant ways: First, it develops a Comprehensive Industrial Pollution Index (IPI) that encompasses all aspects of industrial pollution for Asian countries, specifically focusing on nonrenewable energy consumption, industrial wastewater, industrial waste gases, and industrial solid waste. Second, it delineates each pollution dimension through four distinct indices: a nonrenewable energy consumption index, an industrial wastewater index, an industrial waste gas index, and an industrial solid waste index. Third, the study employs Principal Component Analysis (PCA) to compute these indices. PCA is recognised as a robust and effective method for constructing pollution indices, particularly within the context of Asia. By summarising a wide range of correlated pollution indicators—like industrial emissions, wastewater discharge, energy use, and solid waste—into a more manageable number of independent components, PCA encapsulates the essential information while addressing statistical challenges, such as multicollinearity. This data-driven methodology enhances the objectivity and comparability of pollution indices across various industrial frameworks and economies, making PCA a trustworthy tool for evaluating industrial pollution in the Asian context. Lastly, the paper conducts a comparative analysis of industrial pollution levels and their categories across selected Asian countries. This analysis aims to assist policymakers in understanding the ramifications of human activities on climate change from the perspective of industrial growth. It also provides insights for crafting environmental regulations and calculating optimal ecological taxes to mitigate the environmental impacts stemming from industrialisation.

The structure of the paper is organised as follows. Section 2 provides a comprehensive review of the relevant literature and identifies existing research gaps. Section 3 develops the theoretical foundation of the empirical analysis, followed by Section 4, which details the methodological framework. Section 5 presents and discusses the empirical results. Finally, Section 6 concludes the paper by summarising the key findings and outlining the policy implications derived from the study.

2. LITERATURE REVIEW

Empirical literature has shown that the primary sources of air, soil, and water degradation are exacerbated by nonrenewable energy use, industrial solid waste mismanagement, wastewater, and GHG emissions due to the growth of industrialisation, as presented in Table 1 and in Appendix A1.

A review of prior studies reveals that existing research has largely examined isolated aspects of industrial pollution, focusing mainly on single pollutants such as CO_2 emissions (Elfaki & Heriqbaldi, 2023), wastewater discharge (Razman , et al. 2023), solid waste accumulation (Shah , et al. 2023), or energy consumption (Fahim, et al. 2023). These fragmented approaches overlook the multidimensional and interrelated nature of industrial pollution, thereby limiting understanding of its comprehensive impact on industrial productivity. Moreover, most studies analyse environmental degradation but rarely integrate pollution metrics into productivity frameworks, neglecting the “pollution as input” perspective crucial for assessing green industrial efficiency. To address these gaps, this paper develops a Comprehensive Industrial Pollution Index (IPI) that captures multiple pollution dimensions—non-renewable energy use, industrial wastewater, waste gases, and solid waste—within a unified analytical structure. This integrated approach provides a holistic framework for evaluating how diverse pollution sources collectively influence industrial performance and sustainability.

Table 1

Literature Review on Different Dimensions of Industrial Pollution

Author	Country/Region	Methodology	Industrial Pollutant	Findings
Ozkan & Okay (2024)	20 emerging and developed countries	Pooled Mean Group (PMG) (1990–2018)	Energy Consumption	Non-renewable energy consumption degrades the environment
Iqbal et al. (2024)	China	NL-ARDL (2005–2021)	Waste Gas	Increasing climate Policy uncertainty results in lower CO2 emissions.
Razman, et al. (2023)	Southeast Asian Countries	Sampling Method: PRISMA approach	Wastewater	Convective sludge dryers and anaerobic aerobic-wetland sequential systems efficiently purify industrial wastewater.
Shah, et al. (2023)	OECD Economies	Empirical Study (2000-2020)	Solid waste	Industrialisation and economic expansion led to an increase in solid waste in OECD economies.
Elfaki & Heriqbaldi (2023)	Indonesia	ARDL (1983-2018)	Waste Gas	The moderating effect of industrialisation does not support the EKC hypothesis. Although economic growth has a substantial negative influence on CO2, economic growth squared is positively correlated with CO2 emissions.
Dissanayake, et al. (2023)	152 countries developed	Panel Granger-causality test (1990–2019)	Waste Gas	Developed nations emit more CO2 because they depend more on nonrenewable energy sources.
Fahim, et al. (2023)	ASEAN Region	Secondary research examination (2016–2025)	Energy consumption	It is possible to decarbonise the energy system in the ASEAN region.
Yi, et al. (2023)	Thailand	Novel dynamic autoregressive distributed (1980–2018)	Energy Consumption	Short-term CO2 emissions are statistically negatively impacted by renewable energy.
Liu & Lü (2023)	China	GARCH-MIDAS model (2018–2022)	Waste Gas	Climate policy uncertainty significantly affects the term variations in carbon neutrality.
Raihan & Voumik (2022)	Malaysia	Dynamic ordinary least squares (DOLS)	Energy Consumption	Non-renewable energy and CO2 emissions are positively correlated

Continued-

Author	Country/Region	Methodology	Industrial Pollutant	Findings
Ahmed, et al. (2022)	55 countries of the Asia-Pacific region	autoregressive distributed lag (ARDL) model (1995-2020)	Energy Consumption	FDI has a detrimental effect on the environment and raises CO2 and methane emissions. Industrialisation is positively correlated with the environment. The pollution heaven and environment Kuznets curve (EKC) hypotheses are accepted.
Nidheesh, et al. (2022)	Developing Countries	Experimental Study	Wastewater	Industrial wastewater is a major source of water pollution. However, integrated or hybrid technology is best for industrial wastewater purification.

3. THEORETICAL FRAMEWORK

Our theoretical framework builds upon the "pollution as input" approach developed by Baumol & Oates (1988), which conceptualises pollution not merely as a residual by-product of production but as a scarce economic input or factor of production. In this perspective, ecological resources—such as air, water, and soil—are implicitly consumed in the industrial production process through the generation of pollutants and emissions. For this study, industrial pollutants are employed as proxies for ecological resource consumption in Asian industries, allowing us to capture the intricate link between environmental degradation and industrial growth. The central argument is that ecological resources are being exploited as unpaid inputs in production. Since industries do not fully compensate for their ecological usage, environmental degradation persists as an externalised cost. This dynamic enables short-term industrial growth but jeopardises the long-term sustainability of the growth process. If ecological resources continue to be treated as free and unaccounted factors of production, the resulting degradation will undermine both economic performance and social welfare in the future. Consequently, accurate measurement and valuation of industrial pollutants are crucial for optimising ecological resource use while sustaining growth.

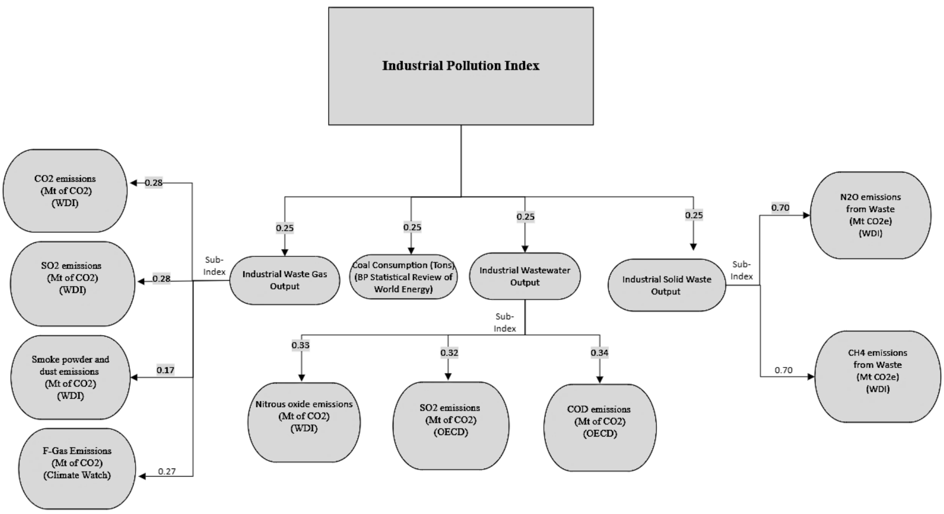
Theoretical analyses of the interaction between growth and the environment have historically demonstrated a positive association between pollution and industrial productivity (Bovenberg & Smulders, 1995; Brock & Taylor, 2005; Considine & Larson, 2006; Mohtadi, 1996; Smulders & Gradus, 1996; Tzouvelekas, et al. 2006; Xepapadeas, 2005). Notably, Chimeli & Braden (2005) explored the relationship between Total Factor Productivity (TFP) and the Environmental Kuznets Curve (EKC), suggesting that productivity gains may initially coincide with environmental degradation before improving at higher levels of income. Similarly, Kalaitzidakis, et al. (2006) employed an empirical analysis linking TFP and CO_2 emissions, treating TFP as the dependent variable and emissions as an explanatory factor. Their findings confirmed an association between productivity and emissions but were limited by their narrow focus on CO_2 alone, thereby neglecting other important forms of industrial pollutants. By extending this theoretical perspective beyond CO_2 emissions to a broader range of industrial pollutants, our analysis emphasises the systemic exploitation of ecological resources as unpaid factors of production in Asian economies. This broader framework allows for a more comprehensive understanding of the pollution–growth nexus and highlights the urgent need for policy interventions aimed at aligning industrial growth with environmental sustainability.

4. METHODOLOGY

4.1. Measurement of Industrial Pollutants

Based on empirical literature and various dimensions of industrial pollution, we categorised environmental impacts of industrial activities into two subcategories: energy consumption and ecological use. To assess the ecological use by industrialisation, we constructed three main indices as indicators of industrial pollution: the industrial waste gas index, the industrial wastewater index, and the industrial solid waste index. Due to the unavailability of data on industrial solid waste in the sample countries, we used data on nitrous oxide and CO2 emissions from industrial solid waste as a proxy. We selected these dimensions based on their relevance to the subject, comprehensiveness of ecological impacts, data accessibility, and representativeness. Figure 2 illustrates the assessment system used to describe the process through which the overall Industrial Pollution Index (IPI) and its four sub-indices are constructed. All indicator data were normalised using the min-max approach, with values ranging from 0 to 100. The Principal Component Analysis (PCA) method determined the weights applied to calculate the indices, as shown in Figure 2.

Fig. 2. Measurement of Industrial Pollution Index (Authors' Construct)



4.2. Comparison of Objects and Data Sources

We selected thirteen Asian countries—Pakistan, India, Indonesia, China, Japan, Singapore, Malaysia, South Korea, Thailand, Bangladesh, the Philippines, Sri Lanka, and Vietnam—based on data availability from the Asian Productivity Organisation (APO). The panel spans 2001–2023, capturing recent developments in industrial activity and environmental regulations, with data sourced from UNIDO, WDI, the Statistical Review of World Energy, and Penn World. Missing values were addressed using linear interpolation, extrapolation, and moving average techniques to create continuous series, minimising bias and ensuring robust computation of the Comprehensive Industrial Pollution Index (IPI). This coverage provides sufficient temporal and cross-country breadth for long-run analysis, with all variable details summarised in Table 2.

Table 2

Variables, Measurement, and Data Sources

Variables	Measurement	Data Source
	Energy Index	
Coal Consumption	Tons	BP Statistical Review of World Energy June 2022
	Wastewater Index	
Chemical oxygen demand (COD) emissions	Millions of tons of CO2	BP Statistical Review of World Energy June 2022
Ammonia nitrogen emissions	Millions of tons of CO2	WDI
Carbon dioxide emissions from fuel combustion	millions of tons	UNIDO Statistics
	Waste Gas Index	
SO2	Millions of tons of carbon dioxide equivalent	BP Statistical Review of World Energy June 2022
CO2 emissions	Millions of tons of carbon dioxide equivalent	WDI
Fluorinated gases (F-gases)	Millions of tons of CO2	WDI
Smoke powder and dust emissions	percent of total fuel combustion	WDI
	Solid Waste Index	
Nitrous oxide (N2O)	Millions of tons of carbon dioxide equivalent	WDI
CO2 emissions	Millions of tons of carbon dioxide equivalent	WDI

4.3. Index Composition

4.3.1. Data Normalisation

The main challenge in constructing an index is finding an effective aggregation method to combine multidimensional sub-indicators into a composite index. Normalisation is a key process that transforms complex datasets into simpler forms, often known as data rescaling. The min-max normalisation technique is popular for this purpose as it linearly transforms data while preserving relationships and correlations among variables, allowing for comparability despite different units of measurement. The formula for normalisation is given as

$$\frac{(G_v)_{i,t} - (Min_v)_{i,t}}{(Max_v)_{i,t} - (Min_v)_{i,t}} \times 100$$

G_v = Given value, Min_v =Minimum values, and Max_v =Maximum values. The index ranges from zero to one hundred.

4.3.2. Setting the Index Weights

The main issue of a thorough assessment is assigning the appropriate index weight coefficient.

The weights of the indices are established using the Principal Component Analysis (PCA). PCA, initially introduced by Pearson (1901) and often attributed to Hotelling (1933), is a statistical method used to examine the relationships among indicators to identify their underlying structure. It is a non-parametric technique that assumes the data is a linear combination of related variables, with components of higher variance reflecting important dynamics. Previous studies have applied PCA to determine variable weights and structures, combining sub-indicators to create a composite index that retains maximum common information (Nardo, et al. 2005). Organisations like the World Bank and UNIDO have widely used this technique to simplify large data sets into fewer composite variables. The components are uncorrelated, with the first principal component explaining most of the data variability, leading to weight assignments based on this component (Fernando, et al. 2012). Weights can be determined by the following formula

$$w_{i,j} = \frac{C_{i,j}}{\sum_{j=1}^{n} S_{i,j}} \times 100$$

Let $i = 1,2, \dots, m$denote the number of indices and $j = 1,2, \dots, n$the number of indicators. In PCA, $C_{i,j}$represents the score coefficient of the jth variable in the first principal component of the ith index, while $w_{i,j}$is the corresponding weight. Each numerical variable receives a unique weight based on its contribution to the first principal component, which captures the maximum variance in the data and summarises the most important information. PCA transforms correlated variables into uncorrelated components (orthogonal), reducing dimensionality and ensuring data-driven, objective weight assignment rather than arbitrary weighting. Variables are combined linearly as

$$y_t = \alpha_{11}x_1 + \alpha_{12}x_2 + \cdots + \alpha_{1\rho}x_\rho$$

where $\rho$is the number of main components. Eigenvalues indicate the variance explained by each component, with the first component capturing the largest share. After determining weights and computing sub-indices using min-max normalisation, the composite index is developed. Each composite index representing weights and sub-indices for nation I in period t is constructed using the generic formula $w_{it} = (w_1\ldots, w_M)$ and $S_{it} = (S_1\ldots, S_M)$ with M sub-indices. This formula can be expressed as follows:

$$C_{it} = \frac{\sum_{m=1}^{M} w^m{}_{it} S^m{}_{it}}{\sum_{m=1}^{M} w^m{}_{it}}$$

This ensures that each variable’s contribution to the index reflects its empirical importance.

4.4. Pairwise Correlation Analysis

To validate the IPI, we conducted pairwise correlation analysis between the IPI and its component indicators. This analysis assesses the internal consistency of the index by confirming that higher values of each pollution component correspond to higher index values. Strong and positive correlations indicate that the IPI effectively aggregates multiple dimensions of industrial pollution as theoretically expected.

5. RESULTS DISCUSSION

5.1. The Pairwise Correlation Analysis

The pairwise correlation results in Table 3 show that the IPI is strongly and positively correlated with all its component indicators (cc = 0.9693, lnw = 0.7867, ln was = 0.7798, lng = 0.6338), indicating that higher values of each pollution dimension correspond to higher values of the IPI, as theoretically expected. These results confirm that the index effectively aggregates multiple dimensions of industrial pollution, and the PCA weighting is consistent with the observed correlations, ensuring a balanced and data-driven measure.

Table 3:

The Pairwise Correlation Estimates

Variables	Energy index	Gas index	Water index	Waste index	IPI
Energy index	1.0000				
Gas index	0.5298 (0.0000)	1.0000			
Water index	0.7048 (0.0000)	0.6552 (0.0000)	1.0000		
Waste index	0.6768 (0.0000)	0.5565 (0.0000)	0.8030 (0.0000)	1.0000	
IPI	0.9693 (0.0000)	0.6338 (0.0000)	0.7867 (0.0000)	0.7798 (0.0000)	1.0000

5.2. Comparative Analysis of Industrial Pollution Levels

According to a comparative analysis of the average pollution levels of sample countries in Table 4 and Fig.3, China has the highest industrial pollution level at 57.40 on average. This high pollution level is primarily driven by its substantial industrial base, particularly in wastewater management and industrial solid waste, underscoring China's role as a major global manufacturing hub. India ranks second with an average pollution level of 24.33, less than half of China's. This notable difference highlights China's larger industrial scale and greater pollution output than India.

Table 4

Average Growth Rate of Various Dimensions of Industrial Pollution

Countries	Industrial Waste Gas	Industrial Wastewater	Industrial Solid Waste	Nonrenewable Energy	Total Pollution
China	46.73	65.36	114.40	4.73	57.40
India	17.81	16.62	62.44	4.12	24.33
Veit	38.34	1.61	6.04	1.78	11.43
Indo	11.81	4.30	16.26	2.77	8.05
Japan	17.42	5.94	8.23	2.08	7.88
Pak	18.11	3.80	9.70	2.26	7.83
Thai	18.52	1.75	5.65	1.72	6.41
Korea	15.75	2.62	5.97	1.78	6.05
Bang	9.36	0.91	7.31	1.98	4.32
Phil	10.09	0.64	5.47	1.69	3.98
Malaysia	12.28	1.12	2.79	1.01	3.98
Sing	11.99	1.80	0.63	0.10	3.53
Sri	4.64	0.14	1.27	0.23	1.44

Vietnam follows in third place with a pollution level of 11.43, mainly due to its high emissions of industrial waste gases, although its overall pollution level is still significantly lower than India's, reflecting a smaller industrial base. Indonesia (8.05) and Japan (7.88) have similar overall pollution levels. Indonesia's contributions mainly come from solid waste and industrial waste gases, while Japan's advanced industrial technologies likely aid in pollution control.

Fig. 3. Average Growth Rate of Various Dimensions of Industrial Pollution

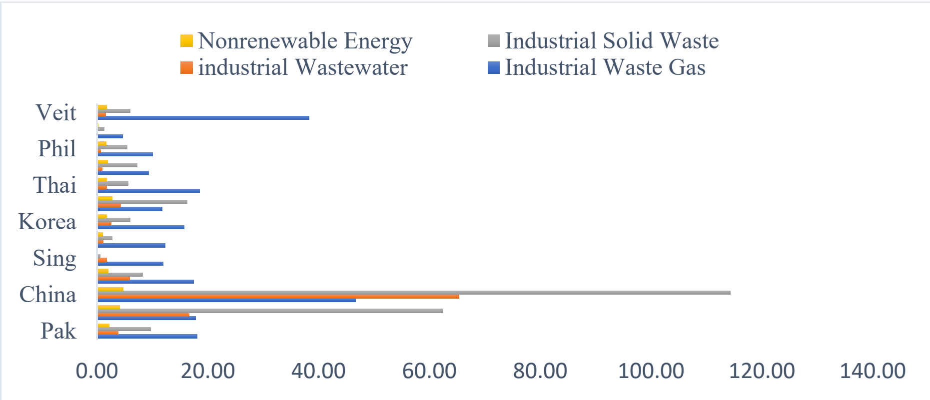


Figure 4 presents the annual trend of the IPI for each selected Asian country, which exhibits similar trends as presented in the average trend of IPI in Table 3 and Figure 3. The disparity between high-pollution countries (China, India) and low-pollution countries (Singapore, Malaysia, Sri Lanka, etc.) highlights regional differences in industrial growth, environmental management, and regulatory enforcement. The sharp increase in China reflects rapid industrialisation and urbanisation, whereas the smaller, gradual increases in other countries indicate slower industrial growth or more effective pollution controls.

Fig. 4. Annual Trend in Overall Pollution Levels in each Sample Country

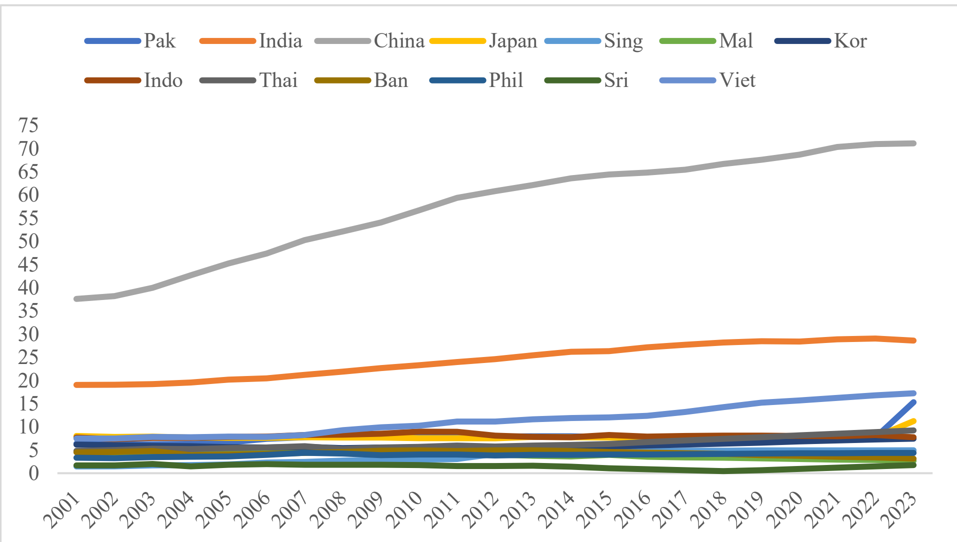


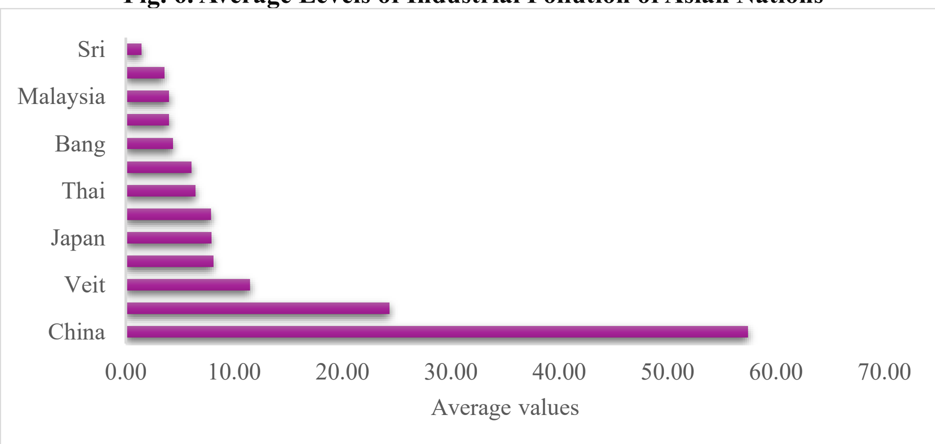
Fig. 5 shows the relative share of our sample countries' industrial pollution contribution in Asia on a map. Pakistan (7.83) and Thailand (6.41) exhibit comparable pollution levels, with Pakistan slightly higher due to larger contributions from solid waste and industrial waste gases. South Korea follows with a pollution level of 6.05, benefiting from its environmental regulations that likely help reduce pollution compared to other nations with similar industrial activity.

Fig. 5. Industrial Pollution Values across Different Countries' Locations

Despite significant contributions from solid waste, Bangladesh (4.32) and the Philippines (3.98) have relatively low pollution levels, indicative of limited industrial operations. Singapore (3.53) and Malaysia (3.98) also show low growth rates of overall pollution. Singapore's particularly low pollution growth is attributed to its heavy reliance on renewable energy technologies and minimal industrial solid waste. The country with the lowest overall pollution level is Sri Lanka (1.44), known for its small industrial base and low contributions from all pollution categories.

In brief, Fig.6 shows that countries with high pollution levels, such as China and India, reflect their extensive industrial bases and resource-intensive economies. In contrast, countries like Vietnam, Indonesia, Japan, Pakistan, and Thailand serve as examples of mid-level polluters, representing varying degrees of environmental management and industrial development. Singapore and Sri Lanka exemplify low-polluting nations with effective environmental regulations or modest industrialisation.

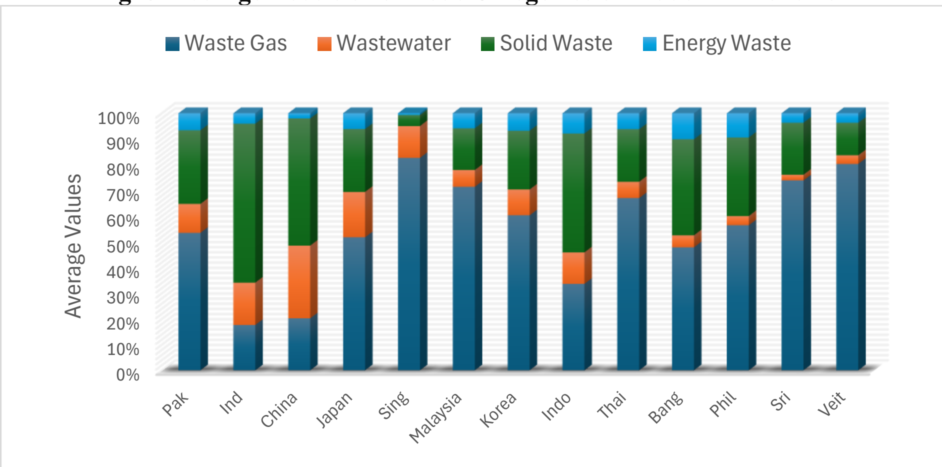
Fig. 6. Average Levels of Industrial Pollution of Asian Nations



5.3. Comparative Analysis of Various Categories of Industrial Pollution

The comparative analysis of different categories of industrial pollution in Fig.7 shows how various nations' industrial operations, economic development, and environmental legislation all contribute to industrial pollution.

Fig. 7. Average Levels of Various Categories of Industrial Pollution

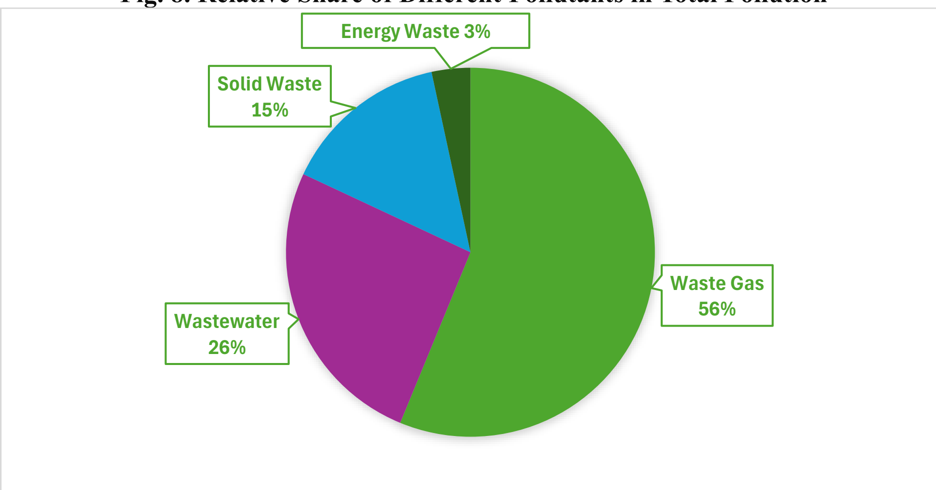


China's industrial solid waste (114.40) is disproportionately high, making it the primary contributor to pollution. Additionally, wastewater (65.36) and industrial waste gas (46.73) are also significant contributors. The heavy industrialisation of China, combined with its reliance on nonrenewable energy sources (4.73), further exacerbates its environmental impact. India, which has the second-highest pollution level (24.33), primarily experiences pollution from solid waste and energy emissions. The main contributors to India's pollution include wastewater (16.62), waste gas (17.81), and solid waste (62.44). The significant population, growing industrial base, and energy-intensive economy of India are reflected in its pollution levels.

Industrial waste gas is the primary driver of pollution in Vietnam, contributing significantly to 38.34 percent of total emissions. The figure highlights the country's heavy reliance on sectors such as manufacturing and power plants, which emit large quantities of air pollutants. In Indonesia, the major contributors to pollution are waste gas (11.81 percent) and solid waste (16.26 percent), along with moderate wastewater emissions (4.30 percent). This pattern indicates a lower energy footprint and medium-level industrial activity. In Thailand, waste gas (18.52 percent) is also the primary cause of pollution, although other categories remain low, resulting in a moderate overall pollution level. Korea maintains balanced contributions to pollution, with solid waste (5.97 percent), wastewater (2.62 percent), and waste gas (15.75 percent), reflecting effective pollution control measures. Malaysia and the Philippines have comparable pollution levels (3.98 percent) due to waste gas and solid waste, indicating smaller but significant industrial sectors. Due to their heavy reliance on fossil fuels, Thailand, Indonesia, the Philippines, Vietnam, and Malaysia are major contributors to the region's energy-related CO_2 emissions (Kisswani, et al. 2024). Japan exhibits a more balanced pollution profile, with wastewater accounting for 5.94 percent, waste gas at 17.42 percent, and solid waste at 8.23 percent. The country's high industrial output is likely regulated by its advanced environmental policies and technologies. In Pakistan, the main pollution drivers are solid waste (9.70 percent) and industrial waste gas (18.11 percent), indicating moderate pollution from energy use and wastewater. Pakistan implemented environmental regulations through its National Environmental Policy in 2005. Based on these indicators, Vietnam, Indonesia, Japan, and Pakistan can be categorised as medium-pollution countries.

In Bangladesh, the primary pollution contributors are industrial solid waste (7.31 percent) and energy-related pollution, which highlight the waste management difficulties faced by expanding businesses. Many open dumps in Bangladesh are located on low-lying terrain, leading to issues during periods of intense rainfall and flooding. The Ministry of Environment and Forests in Bangladesh has established some solid waste handling guidelines, but solid trash is often dumped at landfills without treatment or controls, resulting in major environmental problems. Some organic waste is utilised in composting processes (Glawe, et al. 2005). In Singapore, waste gas accounts for 11.99 percent of total emissions, while other categories, such as solid waste, contribute only 0.63 percent. Major industries in Southeast Asia that produce significant amounts of waste include basic metals, tobacco products, wood and wood products, and paper and paper products, particularly in Singapore and Malaysia. In 2000, Southeast Asian countries produced an estimated 19 million tons of industrial waste (Hotta, 2010). In contrast, all forms of pollution are low in Sri Lanka, which exhibits minimal industrialisation. Fig. 8 shows that the main causes of overall industrial pollution in these countries are waste gas, wastewater, and industrial solid waste, rather than non-renewable resources.

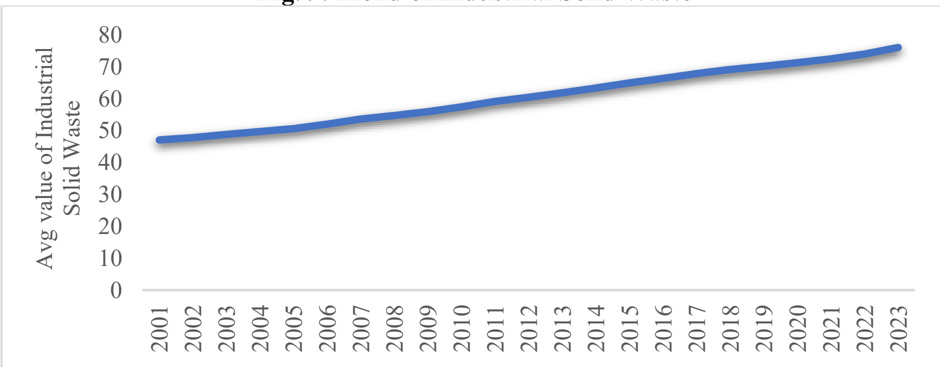
Fig. 8. Relative Share of Different Pollutants in Total Pollution



5.3.1 Industrial Solid Waste

Industrial waste is waste generated by production processes in factories, mills, and mines. It emerged after the Industrial Revolution. A large portion of industrial waste, such as waste fiber from forestry and agriculture, is neither toxic nor dangerous. Industrial operations in the manufacturing sector result in the generation of several waste streams, such as chemical waste and toxic waste. Despite national and international commitments to minimising industry waste, waste from the industrial sector is still increasing over time, as indicated by Fig. 9.

Fig. 9. Trend of Industrial Solid Waste



The most widely used technique of treating solid waste in Southeast Asian nations is open landfills. Open landfills have been used for many years to manage waste because they provide a solution to the massive amounts of daily produced rubbish. Being an economical method for treating solid waste and the amount of organic material in it, this approach is widely used. However, most ASEAN landfills are unsanitary open dumping sites without perimeter control, clay-lined layers, gaseous migration systems, a leachate management system, a geo-membrane liner system at the bottom of the landfill, etc. Open dump sites remained the most affordable and efficient way to dispose of the growing volumes of garbage, even if governments have started to establish sanitary landfill sites in a few urban areas. However, compared to open dumpsites within municipal bonds, sanitary landfills are frequently situated too far away from generators. Such sites have higher transfer costs and necessitate more infrastructure investments to approach distant trash-producing sources. Furthermore, waste is frequently dumped along the side of the road or tossed straight into rivers and waterways. Without any preparations from an environmental standpoint, it is unknown how much waste is disposed of in the open, particularly in rural areas. Lack of funding, difficulties acquiring land, and an inadequate trash collection and transfer system are the causes of these issues. Besides this, incineration is used to treat waste. Singapore and other nations have effectively used this technique. Malaysia, for instance, currently operates one municipal incinerator in a nearby suburb and intends to build another in Kuala Lumpur. Both Thailand and Indonesia have a single municipal garbage incinerator in their main cities. Because of the issue of gas emissions from the incinerators, there is still debate on the viability of incineration. The substances of concern are specifically persistent organic pollutants (POPs- dioxins, furan, PCBs, hexane, etc.). For this reason, recent waste management legislation in the Philippines, for example, has outright prohibited waste incineration.

Regarding waste recycling, about 44.4 percent of solid trash in high-income nations like Singapore gets recycled. Approximately 12 percent of garbage is recycled in middle-income nations and 8–11 percent in the remaining ASEAN nations. While many countries have legislation about waste management, most of them do not cover waste management in its entirety, as laws on stormwater management are particularly lacking. Most ASEAN nations lack a strong institutional framework for waste management. Although certain government organisations are required to oversee various waste industries, their functions and responsibilities are undefined. The impact of trash is also becoming more prominent due to a shortage of resources, particularly funding, technologies, capacity, and waste management skills (Ngoc & Schnitzer, 2009).

5.3.2. Industrial Effluent

The liquid waste produced by industrial processes is referred to as industrial effluent. Asia is severely impacted by industrial effluence, which influences water quality and environmental health throughout the region.

Fig. 10. Over-time Trend of Wastewater Production in Asia

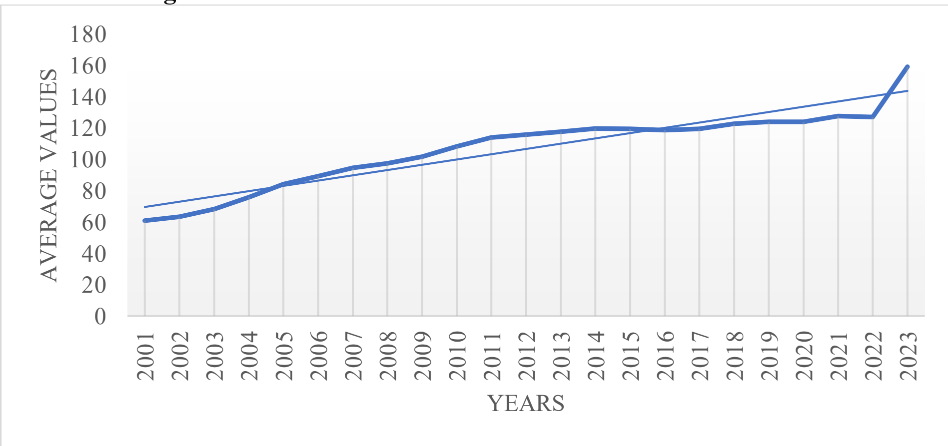


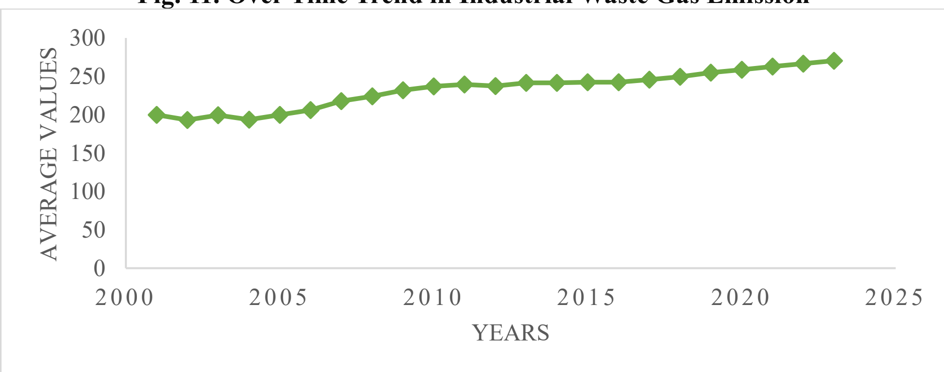
Fig. 10 shows that wastewater creation in our sample has surged due to rapid industrialisation, posing severe dangers to human health and ecosystems if untreated (Samriti, et al. 2023). These issues are made worse by ineffective laws and enforcement, especially in developing countries, where industrial development outpaces environmental governance (Chakraborty & Mukhopadhyay, 2014). Chemicals or solid pollutants can be found in aquatic environments due to anthropogenic contamination, industrial waste, and leaks (Kreisberg, 2005). Surface waters are contaminated by fertilisers and detergents that contain phosphorus and nitrates, which serve as nutrients and promote the growth of oxygen-consuming algae. This lowers the dissolved oxygen (DO) levels in the water, killing fish and other aquatic life (Crane, et al. 2006). Paper mills, breweries, tanneries, slaughterhouses, petroleum refineries, and other commercial and industrial effluents pollute the water with organic contaminants and releasing organic contaminants that lower DO levels, negatively impacting fish and other species. Thermal pollution further exacerbates this issue (Stanley, et al. 2007). High nitrogen levels often lead to excessive algal blooms, diminishing the recreational value of surface water and causing mass fish fatalities. Asia, particularly India, faces severe water shortages and pollution, especially in the heavily contaminated Yamuna River, exacerbated by rubbish disposal because of its rapid industrialisation and poor waste management (Akbal, et al. 2011). This leads to health risks, nutrient depletion, and declines in water quality, alongside increased environmental pollution from industrial effluents.

Ammonia and nitrous oxide are harmful forms of nitrogen commonly found in wastewater. Consuming water with nitrates can lead to methemoglobinemia or blue baby syndrome in vulnerable individuals (Mohammadi, et al. 2020). Hydrocarbon pollutants in wastewater threaten fisheries, marine habitats, human health, and ecological balance. Chemical Oxygen Demand (COD) is toxic, even in low amounts, endangering aquatic life and human health. In Bangladesh, river pollution has been linked to cases of scabies (Arif, et al. 2020). Minamata is a well-known case of mercury poisoning in Japan. The characteristics of rivers receiving industrial effluents can indicate their environmental health, significantly impacting aquaculture and fisheries. The Brahmaputra River, often known as the Discharge, is the largest river in Tibet and in the world. Qadir et al. (2020) estimated that 380 billion m3 of wastewater is created globally each year. It is predicted that the amount of wastewater generated every day will rise by 51 percent (574 billion m3) by 2050 and by 24 percent (470 billion m3) by 2030, considering the rate of urbanisation and population growth. Notably, Asia accounted for 42 percent (159 billion m3) of global wastewater production, making it the region with the highest output. Wastewater output is predicted to increase by 44 percent by 2030; therefore, it should be acknowledged as a part of the environmental factor in industrial production with the cost factor.

5.3.3. Industrial Waste Gas

Air pollution refers to harmful substances in the atmosphere that can damage ecosystems, the environment, and human health. Common air pollutants include gases like carbon dioxide, sulfur oxides, and nitrogen oxides, as well as aerosol pollutants like dust and bacteria. Routine air quality monitoring typically includes ozone (O3), sulfur dioxide (SO2), nitrogen dioxide (NO2), and particulate matter (PM2.5 and PM10). Industrial waste gas significantly impacts public health, particularly through inhalable particles. Particles less than 10 mm (PM10) can enter the lower respiratory tract, with those smaller than 2.5 mm (PM2.5) reaching the lungs' alveoli and potentially causing long-term health issues. In Europe, PM2.5 contributes to numerous deaths and reduces life expectancy by an average of 8.6 months, according to official statistics from the World Health Organisation (WHO) (Orru, et al. 2011). In China, rapid urbanisation and high population have led to inadequate air pollution management, resulting in severe air quality issues, especially in densely populated and economically advanced regions (Zhou, et al. 2018). Air pollution from industrial waste gas poses a significant threat to sustainable growth in Asia. The increase in emissions, as shown in Fig. 11, will adversely affect agriculture, industry, and transportation, damaging soils, crops, and infrastructure due to acid deposition from compounds like SO2 and NO2.

Fig. 11. Over Time Trend in Industrial Waste Gas Emission



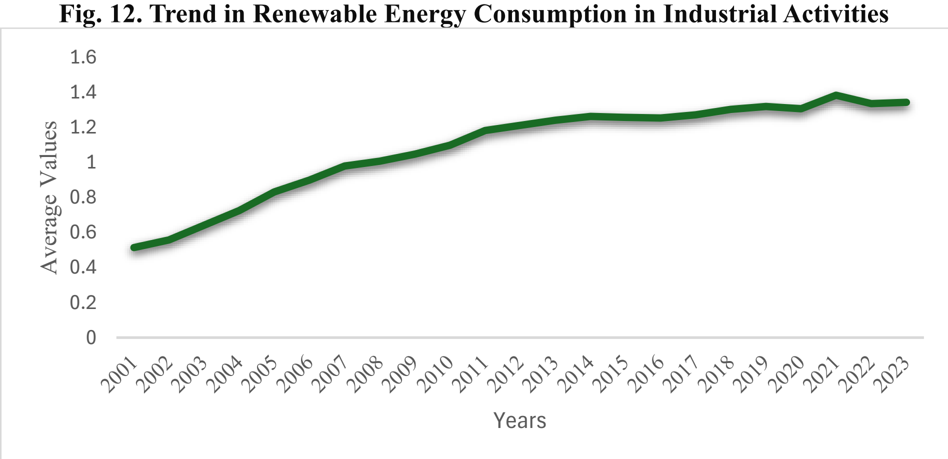
This pollution also disrupts climate patterns, leading to increased droughts and floods. Extensive research has been conducted on the environmental and health impacts of industrial waste gas. They also investigated the financial losses caused by industrial waste gas. For instance, ApSimon, et al. (1994) investigated the effects of industrial waste gas across Europe, with a focus on SO2. Because it was difficult to restrict its movement, they discovered that the impact of air pollution was quite broad, affecting not just local areas but also national and regional political decisions. Quah and Boon (2003) developed an air pollution cost function to examine the relationship between the country's morbidity and death rate and airborne particulate matter in Singapore. According to their calculations, the economic cost of air pollution in 1999 was around 4.31 percent of its GDP for that year. Ikefuji, et al. (2014) found that buildings, agricultural output, and human health would all be impacted by climate and environmental change due to air pollution, including haze-fog and other extreme weather conditions. Fu and Chen (2017) examined China's air pollution since 2013 from the perspective of rising medical costs. Researchers discovered that air pollution has led to a rise in patients with both acute and chronic respiratory conditions, which has raised medical expenses and reduced overall social welfare.

Methods for treating and controlling air pollution caused by industrial waste gases have been studied since Pigou (1920), who first applied the externality theory to environmental issues. He identified the imbalance between the costs borne by polluting industries and the broader social costs incurred by society due to pollution. Pigou argued that since polluters did not have to pay for their emissions, the government should impose taxes on these facilities proportional to the harm they inflict on society. Building on Pigou's foundation, Pan, et al. (2024) suggested that a combined approach utilising market mechanisms, including taxation and emission trading, could effectively mitigate the negative externalities associated with industrial outputs. This market-based approach allows for the adjustment of industrial emissions through tax mechanisms (Du & Zhou, 2022). Tu, et al. (2020) emphasised that a successful implementation of emission trading requires accurately identifying and valuing the emission rights of different industrial entities. Without meeting these fundamental prerequisites, effective market-based trading and control of industrial waste gas pollution cannot be achieved.

5.3.4. Industrial Energy Consumption:

In recent decades, carbon dioxide (CO_2) emissions have emerged as the main cause of global warming. This phenomenon is mostly caused by the sharp rise in human activities that emit CO_2 into the atmosphere, mostly from burning fossil fuels like coal, oil, and natural gas, as well as deforestation, agricultural practices, and cement manufacture. Dissanayake, et al. (2023), using data from 152 nations,

Fig. 12. Trend in Renewable Energy Consumption in Industrial Activities



discovered that industrialised countries emit significantly more CO2 than developing countries because they use a larger percentage of non-renewable energy in their overall energy consumption. Energy use raises carbon (CO2) emissions, which impact climate change and environmental deterioration (Iqbal, et al. 2023). Fig.12 shows the time trend of renewable energy consumption in our sample countries. China's CO2 emissions are also positively impacted by using non-renewable energy. Because energy use to support economic growth would raise CO2 emissions (Farooq, et al. 2023).Energy use has a positive effect on carbon emissions, which lowers the environmental quality of South Asian nations (Batool, et al. 2022). The usage of renewable energy lowers CO2 emissions in Brazil, China, Indonesia, India, Mexico, Turkey, and Russia (Husnain, et al. 2022). Renewable energy usage is positively associated with lower carbon emissions.

The Association of Southeast Asian Nations (ASEAN) region has seen significant socioeconomic changes over the past 20 years, making its countries some of the most impacted by climate change worldwide. Rapid urbanisation, industrialisation, and an ongoing increase in energy demand have all contributed to the significant economic and demographic growth of the ASEAN region. The GDP of ASEAN members is expected to rise faster than that of other advanced and emerging nations. Their GDP is anticipated to increase at an average rate of 6.2 percent until 2027, outpacing the most advanced and developing countries (Imperial College London, 2023). Vietnam, Malaysia, Cambodia, and Indonesia are notable leaders in this economic expansion. This quick growth naturally results in high energy consumption and pollution. Asia is responsible for 60 percent of the world's population, 52 percent of global agricultural production, and 43 percent of greenhouse gas (GHG) emissions (Asian Development Bank, 2023). Additionally, according to Mamat et al. (2019), the energy demand of Southeast Asian nations has increased by 60 percent in the last 15 years, but their energy sources continue to rely on traditional polluting sources. Due to its high energy intensity and comparatively strong reliance on coal, the region is anticipated to be the main driver of the increase in global greenhouse gas emissions, contributing close to 40 percent of all emissions in 2020 (IMF 2023).

To reduce CO2 emissions, the governments of Southeast Asian nations are encouraging the development of new and renewable energy sources. Environmental concerns and energy availability present a shared dilemma. Vietnam, Thailand, Malaysia, Indonesia, and Singapore are among the nations that have pledged to achieve carbon neutrality or net-zero emissions by 2050. But there is still a long way to go until this goal is accomplished (IMF 2023). The region's long-term energy consumption goals include raising the proportion of renewable energy from 19 percent in 2018 to 65 percent by 2050. According to the International Renewable Energy Agency (IRENA, 2020), this shift is expected to result in a 75 percent decrease in energy-related CO2 emissions as compared to the present policy.

6. CONCLUSION

By conceptualising ecological resources as components of social overhead capital, this study presents a novel approach: treating industrial pollutants—solid waste, waste gas, wastewater, and non-renewable energy use—as proxies for the unpaid use of environmental assets in production processes. While earlier studies have narrowly focused on singular and specific pollutants such as CO_2, this research emphasises the need for a broader, more inclusive assessment of industrial pollution. The proposed comprehensive Industrial Pollution Index enables a multidimensional understanding of how industrialisation exploits ecological systems across selected Asian economies. The empirical analysis highlights that industrial solid waste, wastewater, and waste gas are the predominant contributors to environmental degradation, rather than non-renewable energy consumption in the sample Asian countries. Findings underscore that the ecological impact of industrialisation is not uniform across the region; mid-level industrialised nations such as Vietnam, Indonesia, and Pakistan exhibit mixed pollution profiles reflecting both progress and gaps in environmental governance. The comparative analysis of industrial pollution levels across Asian countries reveals significant disparities in environmental impacts stemming from varied industrial structures, energy dependencies, and regulatory frameworks. China and India emerge as the largest polluters, primarily due to their expansive industrial bases, heavy reliance on non-renewable energy, and substantial outputs of industrial solid waste, wastewater, and gas emissions. Conversely, countries like Sri Lanka and Singapore maintain notably low pollution levels, benefiting from either modest industrialisation or advanced environmental regulations and waste management systems. The empirical findings stress the urgent need for governments and policymakers to reframe environmental accountability through more holistic pollution measurement, stronger regulation, and appropriate ecological taxation. Without such reforms, the continued degradation of unpaid ecological inputs will not only compromise environmental quality but also erode the long-term sustainability of industrial development itself.

Limitations of this study lie in that the proposed industrial pollution index serves as a proxy for the utilisation of natural resources during the production process. Although this approach is novel, it may oversimplify complicated ecological relationships by assuming a linear and uniform link between pollution and ecological depletion. Furthermore, data availability of several determinants of the different categories of industrial pollutants. Future research could disaggregate industrial pollution data by subsectors (e.g., manufacturing, mining, energy production) to identify high-impact industries and tailor policy interventions accordingly.

6.1. Policy Implications

The results of this study highlight several crucial policy implications for controlling industrial pollution and encouraging Asia's economic development to be sustainable:

6.1.1 Tailored National Pollution Control Strategies

The variation in pollution levels between nations emphasises the necessity of context-specific environmental regulations. High-polluting countries like China and India should prioritise investments in cutting-edge waste treatment technologies, bolster enforcement mechanisms, and implement more stringent emission regulations, especially for wastewater and industrial solid waste.

6.1.2. Transition to Sustainable Energy Sources

The cumulative impact of non-renewable energy is significant, even though it was not the dominant source of pollution. Countries with lower pollution levels, such as Singapore, show the advantages of switching to renewable energy, indicating a wider need for governmental incentives, including feed-in tariffs, subsidies, and technology transfer agreements.

6.1.3. Regional Environmental Policy Coordination

Countries in Asia should seek regional cooperation frameworks through ASEAN, SAARC, or other platforms because environmental deterioration is transboundary.

Reaching regional environmental goals can be facilitated by exchanging best practices and harmonising industrial emission requirements.

6.1.4. Enhancement of Waste Management Systems

Bangladesh and Pakistan, two nations with significant solid waste contributions, need to make investments in advanced, regulated garbage disposal systems. This covers the establishment of engineered landfills, waste segregation plans, and recycling campaigns at the local level.

6.1.5. Regulatory Enforcement and Institutional Strengthening

Strong institutions and efficient environmental governance are key to the success of low- and mid-pollution nations like South Korea and Japan. Improving monitoring methods and bolstering regulatory bodies' institutional ability are essential actions that others should follow.

6.1.6. Policy Planning Using Composite Pollution Indices

This study created the Industrial Pollution Index (IPI), a useful tool for policymakers to track and compare pollution trends. Such composite indices should be incorporated by governments into their industrial licensing regulations and environmental impact assessments (EIAs).

6.1.7. Environmental Responsibility of Businesses

Government-led initiatives can be greatly enhanced by the voluntary adoption of green manufacturing methods, open reporting of emissions, and investment in pollution control technologies by industries.

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APPENDIX

A1: Literature Review of Different Dimensions of Industrial Pollution (Continued)

Author	Country/Region	Methodology	Industrial Pollutant	Findings
Batool, et al. (2022)	South Asian countries	Vector error correction methodology (1991–2020)	Energy Consumption	Carbon emissions are positively correlated with energy consumption.
Husnain, et al. (2022)	E7 countries	Augmented mean group (AMG) (1990–2015)	Energy Consumption	CO2 Emissions decrease with renewable energy use.
Yu, et al. (2021)	China	Constructed the EPU index by the Provincial daily newspaper 2008–2011	Energy Consumption	Provincial economic policy uncertainty raises a firm's CO2 emissions and use of inexpensive fossil fuels.
Lin, et al. (2017)	53 countries	FE, RE (1991–2013)	Waste Gas	Industrialization, urbanization level, and urban employment level have a mixed impact on CO2.
Ahuti (2015)	Developing countries	Qualitative (2015)	Waste Gas	The industrial revolution and the electronics industry have decreased CO2 emissions.
Farhani & Ozturk (2015)	China and India	Granger Causality Test (1971)	Waste Gas	Industrial production increases CO2 emissions.
Xu & Lin (2015)	China	ARDL (1990–2011)	Waste Gas	Industrialization and urban population have mixed impacts on CO2 emissions.
Tian, et al. (2014)	China	OLS (2000–2011)	Waste Gas	Industrialization and energy consumption have mixed impacts on CO2 emissions.
Tian, et al. (2014)	China	Input-output analysis (2002–2007)	Waste Gas	Heavy industries increase CO2 emissions.

Author	Country/Region	Methodology	Industrial Pollutant	Findings
Wang, et al. (2014)	China	OLS (1995–2007)	Waste Gas	Industrialization and energy consumption have mixed outcomes on CO2.
Shahbaz & Lean (2012)	Bangladesh	ARDL (1975–2010)	Waste Gas	Industrialization has mixed impact on CO2.
Dhami, et al. (2013)	India	Environmental input–output analysis	Waste Gas	Industrialization increases CO2 emissions.
Zhou, et al. (2013)	China	SYS-GMM estimates (1995–2009)	Waste Gas	The tertiary industry and secondary industry decrease CO2 emissions through emission-saving technologies.
Mudakkar, et al. (2013)	Pakistan	Granger causality (1975–2011)	Waste Gas	Industrialization and economic growth positively impacted CO2.
Wang, et al. (2013)	China	OLS, ridge regression (1980–2010)	Waste Gas	Industrialization and urban population have a positive impact on CO2
Shahbaz & Lean (2012)	Tunisia	VECM, ARDL (1971–2008)	Waste Gas	Industrialization and financial development have a positive impact on CO2 emissions.
Li, et al. (2012)	China	OLS, ridge regression (1990–2010)	Waste Gas	Industrialization and urban population lead to CO2 emissions.
Zhang & Lin (2012)	99 countries	FE, RE (1975–2005)	Waste Gas	Industrialization has a positive impact on CO2 emissions.
Zhang & Lin (2012)	China	OLS, ARDL (1981–2011)	Waste Gas	Industrialization has mixed impacts on CO2 emissions.

Author	Country/Region	Methodology	Industrial Pollutant	Findings
Al-Mulali and Sab (2012)	92 countries	FMOLS (1975–2005)	Waste Gas	Industrialization positively impacts CO2.
Lin, et al. (2009)	China	OLS (1978–2006)	Waste Gas	Urban population increases CO2 emissions, while industry increases GDP from industry as well as CO2 emissions.
Martínez-Zarzoso, et al. (2007)	EU	FE, RE, GMM (1975–1999)	Waste Gas	Industrialization and urban population rise CO2 emissions.