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Air Pollution Concentrations and Their Determinants in the Top Ten Most Polluted Countries in the World in 2010-2020

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ABSTRACT

This study analyzes air pollution concentration and its determinants in ten countries with the highest levels of air pollution from 2010 to 2020. Air pollution has become a global issue affecting both human health and the environment. The study uses secondary data and applies two analytical tools: a concentration index to identify countries with the highest air pollution levels, and panel data regression to analyze its determinants. Air pollution is proxied by CO2 emissions. The results indicate that eight out of ten countries have a concentration index greater than one, with Japan, South Korea, and Germany ranking as the top three countries with the highest air pollution concentrations. The population variable has a positive and significant impact on air pollution concentration in these countries. Conversely, the energy consumption variable has a negative and significant effect on air pollution concentration. On the other hand, economic growth does not have a significant effect on air pollution concentration. The study's implications highlight the need for a transition to more efficient and renewable energy sources as a crucial step in reducing the negative impacts of air pollution. Stricter environmental policies and increased investments in eco-friendly technologies are highly recommended to address this issue.

Keywords: Air Pollution; Carbon Emission; Economic Growth; Energy Consumption; Population

INTRODUCTION

Since the 1950s, environmental pollution has been a significant and persistent challenge that hinders the path to sustainable development (Santika, 2021; Sazh, 2015). Over the decades, this global issue has been exacerbated by rapid industrialization, urbanization, and increased human activity, which have contributed to the degradation of natural resources and the environment. Among the various forms of environmental pollution, air pollution stands out as one of the most harmful and pervasive consequences. It has shown a significant increase in recent decades, especially in the emission of harmful gases and fine particulate matter that significantly degrade air quality. As a result, air pollution has become one of the leading causes of environmental and health crises worldwide.

According to a report by the World Health Organization (WHO, 2022), ambient air pollution was responsible for 4.2 million premature deaths globally in 2016, underscoring the severe health risks posed by poor air quality. Among these deaths, 58% were attributed to ischemic heart disease and stroke, conditions that are worsened by exposure to pollutants such as particulate matter and harmful gases. Alarmingly, 88% of these premature deaths occurred in countries with relatively low economic conditions, highlighting the disproportionate impact of air pollution on low- and middle-income nations. Within these regions, Southeast Asia emerged as the most affected, accounting for a staggering 1,332,000 deaths from air pollution-related diseases (PAHO, 2018). This data paints a grim picture of the global scale of air pollution and its devastating consequences on public health, particularly in regions that lack the infrastructure and resources to combat environmental degradation.

Between 2010 and 2020, the concentration of several dangerous air pollutants saw a notable increase. These pollutants include particulate matter (PM2.5), carbon dioxide (CO2), carbon monoxide (CO), nitrogen dioxide (NO2), tropospheric ozone (O3), and sulfur dioxide (SO2), with the most significant upticks observed in several countries across Asia and the Middle East. This upward trend can be largely attributed to a combination of unsustainable industrialization, widespread reliance on fossil fuels, and weak or ineffective environmental regulation policies (IQAir, 2023). As industrial activities expanded in these regions, so too did the emissions of harmful pollutants, exacerbating air quality deterioration and posing significant risks to human health and the environment. The increasing trend in pollutant concentrations indicates that without substantial shifts in energy production methods and stricter environmental policies, the global air pollution crisis will only worsen.

Several key determinants contribute to the persistently high levels of air pollution. One of the most significant factors is population growth, which often leads to a higher demand for energy. As populations increase, so does the need for energy to power homes, businesses, transportation, and industries. This surge in energy consumption naturally leads to a rise in emissions, as much of the energy demand is met through the burning of fossil fuels, which release harmful pollutants into the atmosphere (United Nations, 2021). The reliance on fossil fuels for electricity generation, transportation, and industrial processes is a major driver of air pollution, with pollutants such as CO2, sulfur dioxide (SO2), nitrogen dioxide (NO2), and fine particulate matter (PM2.5) being released at large scales (International Energy Agency, 2020). These pollutants not only contribute to the deterioration of air quality but also have far-reaching effects on human health, leading to respiratory diseases, heart conditions, and even premature death (WHO, 2018).

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In addition to population growth, economic development is another critical factor influencing air pollution levels. As nations experience economic growth, industrialization tends to accelerate, and urbanization increases, both of which lead to higher levels of energy consumption and, consequently, higher emissions. The expansion of industries, particularly in the manufacturing and transportation sectors, results in increased demand for energy, much of which is still supplied by fossil fuels. This, in turn, exacerbates air pollution, as emissions from factories, power plants, and vehicles rise in tandem with economic activity (Dilanchiev et al., 2024). This vicious cycle of economic growth fueling pollution, which in turn affects human health and productivity, is a pressing issue that many developing and emerging economies face. As these countries industrialize and urbanize, their environmental footprints grow larger, compounding the challenges of achieving sustainable development (Akazha et al., 2024).

Given these complexities, understanding the precise relationship between energy consumption, economic growth, and population dynamics is essential for tackling the issue of air pollution. The research titled "Air Pollution Concentration and Its Determinants in the Ten Countries with the Highest Air Pollution Levels Worldwide from 2010 to 2020" seeks to delve deeper into these relationships. The objective of this study is to identify the countries with the highest concentrations of CO_2 emissions and to examine how factors such as energy consumption, economic growth, and population density contribute to the observed levels of air pollution. By focusing on the ten most polluted countries, this research aims to provide valuable insights into the specific drivers of air pollution in these regions and to assess the role of various determinants in shaping the trajectory of air quality over time. Through this investigation, the study hopes to inform policy decisions and strategies that can help mitigate air pollution and promote cleaner, more sustainable development pathways for the most affected countries.

LITERATURE REVIEW

The study by Apergis et al. (2023) provides a comprehensive analysis of Uzbekistan's energy consumption and its impact on CO_2 emissions. Using the Autoregressive Distributed Lags (ARDL) model, the study aimed to examine the relationship between energy consumption—both renewable and non-renewable—and CO_2 emissions over both short and long-term periods. The findings from this research revealed that hydropower consumption had a significant negative impact on per capita CO_2 emissions in both the short and long term. This suggests that increasing the use of hydropower, a renewable energy source, can effectively reduce the carbon footprint of the country. Conversely, the study found that natural gas and oil consumption had a positive impact on CO_2 emissions in both time frames. The reliance on these non-renewable energy sources contributes to higher levels of emissions, exacerbating environmental challenges. The study underscores the importance of transitioning towards renewable energy sources like hydropower to mitigate the adverse effects of energy consumption on CO_2 emissions in Uzbekistan, providing crucial insights for policymakers aiming to develop sustainable energy strategies.

In another study, Zikirya et al. (2021) explored the intricate relationships among CO_2 emissions, air pollution, and tourism across 30 Chinese provinces. Utilizing panel data testing, the study examined how these factors interact and influence one another. The results were revealing, showing that CO_2 emissions had opposing effects on domestic and international tourist arrivals. Specifically, while higher emissions deterred international tourists, they appeared to have less of an impact on domestic tourism. This suggests that international tourists may be more sensitive to environmental factors, such as air quality and pollution, than domestic tourists. Furthermore, both domestic and international tourism were found to positively influence CO_2 emissions, as increased

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tourism activity typically leads to higher transportation emissions and greater energy consumption. The study also highlighted the negative effects of particulate matter (PM2.5, PM10) and sulfur dioxide (SO_2) on the number of tourists, indicating that poor air quality can significantly deter tourism. This research emphasizes the need for sustainable tourism policies that balance economic growth from tourism with the imperative to reduce air pollution and CO_2 emissions.

The research by Yakin et al. (2024) analyzed data from all provinces in Indonesia using the Error Correction Model (ECM) method. This study aimed to explore how key economic and energy consumption variables, such as GDP, coal exports, and fossil energy consumption, affect air pollution levels, specifically focusing on CO_2 emissions. The findings demonstrated that in both the short and long term, these variables collectively had a significant impact on CO_2 emission levels. The positive relationship between GDP and CO_2 emissions suggests that as Indonesia's economy grows, energy consumption—and consequently, emissions—tend to rise. Similarly, the significant impact of coal exports and fossil energy consumption on emissions highlights the country's dependence on carbon-intensive energy sources, which contribute to higher pollution levels. This research sheds light on the challenges faced by developing countries like Indonesia, where economic growth and industrialization often come at the expense of environmental sustainability. The study advocates for policies that promote cleaner energy alternatives and more efficient use of resources to reduce CO_2 emissions while supporting economic development.

Finally, the study by Liu et al. (2022), took an expansive approach by examining air pollution and its effects on public health across 205 cities in 20 countries. Using a two-stage time series analytical approach, the research revealed a direct link between coarse particulate air pollution and daily mortality rates. The study found that cities that implemented integrated emission reduction policies experienced significant improvements in air quality. These improvements were accompanied by simultaneous reductions in CO_2 emissions, indicating the dual benefits of such policies in both public health and environmental outcomes. The findings underscore the importance of comprehensive, multi-faceted approaches to pollution control that target both the reduction of particulate matter and CO_2 emissions. By demonstrating the health benefits of reducing air pollution, this study provides strong evidence for the need for coordinated efforts at local, national, and global levels to tackle the urgent challenges posed by air pollution and its adverse effects on public health.

Together, these studies provide valuable insights into the complex relationships between energy consumption, CO_2 emissions, air pollution, and public health across different countries and regions. Each study highlights the critical role that policy interventions, energy choices, and sustainable practices play in mitigating the negative effects of CO_2 emissions and improving air quality. They also emphasize the need for a holistic approach to environmental management that addresses both the causes and consequences of pollution, with a focus on long-term solutions that balance economic growth with environmental sustainability.

RESEARCH METHOD

The data used in this study are secondary data in the form of panel data, combining cross-sectional and time-series data. The data were obtained from two sources: Our World in Data and The World Bank. Data processing was conducted using Eviews 13. This study employed two analytical methods: a concentration index to determine air pollution concentration in the ten countries with the highest levels of air pollution in the world from 2010 to 2020, and panel data regression analysis to identify the determinants of air pollution concentration. The analysis focused solely on the ten countries with the highest air pollution levels: China, the United States, India, Russia, Japan, Indonesia, Iran, Germany, Saudi Arabia, and South Korea.

Operational Definitions of Variables

Air pollution concentration refers to the presence and amount of pollutants in the atmosphere, typically measured in specific units to assess environmental quality and public health risks. In this study, air pollution is represented by carbon dioxide (CO_2) emissions, which are a significant contributor to global warming and climate change. The measurement of CO_2 emissions in this context is expressed in million tons, providing a quantitative assessment of pollution levels across regions or countries. This metric is crucial for evaluating the environmental impact of human activities and industrial processes, as well as for developing strategies to mitigate pollution and its associated effects.

Energy consumption represents the total amount of energy utilized by individuals, institutions, or various activities within a country for purposes such as transportation, industry, residential needs, and commercial operations. In this study, energy consumption is specifically focused on primary energy consumption, which includes energy derived directly from natural resources such as coal, oil, natural gas, wind, and solar energy. It is measured in terawatt-hours, reflecting the scale and intensity of energy usage within a given country. Understanding energy consumption patterns is vital for analyzing their contribution to economic activities and their impact on environmental sustainability.

Economic growth is defined as the increase in a country's or region's production capacity over a specified period. It is often used as an indicator of a nation's economic health and progress. In this study, economic growth is measured by the annual percentage change in Gross Domestic Product (GDP), which encompasses the total monetary value of goods and services produced within a country. Monitoring economic growth enables the evaluation of a country's development trajectory, the efficiency of its economic policies, and its ability to improve living standards for its citizens.

Population refers to the total number of individuals residing within a specific geographic area during a given period. This study considers the population variable as the total number of people in a country, measured in absolute numbers of individuals. Population size and growth are critical factors influencing various aspects of societal development, including resource consumption, economic activities, and environmental impact. By analyzing population data, policymakers can better understand demographic trends and their implications for planning and sustainable development.

Data Analysis Methods

Air Pollution Concentration Analysis

To determine the concentration of air pollution in each country, the Concentration Index formula is used. This index is a tool to assess the concentration patterns within a given region. The concentration index formula is based on a geographical concentration model by adjusting its constituent variables.

$$CI = \{(ECO2c/GHGc)/\ (ECO2g/GHGg)\}$$

Description:
CI = Concentration Index
ECO2c = CO_2 Emissions of the Country GHGc = Greenhouse Gases of the Country ECO2g = Global CO_2 Emissions

GHGg = Global Greenhouse Gases

The concentration index (CI) calculation provides a useful framework for assessing the relative contribution of a country to global CO2 emissions among the ten nations with the highest levels of air pollution. The results are categorized into three distinct levels, each reflecting the country's role in global air pollution dynamics.

Firstly, when the CI is greater than 1 (CI > 1), it indicates that the country plays a significantly larger role in producing CO2 emissions compared to other nations within the top ten highest polluters. This level suggests that the country is a major contributor to air pollution, making it a key player in the global challenge of addressing CO2 emissions and their associated environmental impacts. The larger the CI, the more disproportionate the country's emissions are relative to its counterparts.

Secondly, a CI value equal to 1 (CI = 1) signifies that the country’s contribution to CO2 emissions is on par with other nations in the top ten list. In this scenario, the country is neither a disproportionately large nor small contributor to global emissions, sharing the responsibility equally with the other countries ranked at the highest levels of air pollution. It reflects a balanced role in the overall emission landscape, with no single country among the top ten significantly outpacing the others in terms of emissions.

Lastly, when the CI is less than 1 (CI < 1), it indicates that the country plays a smaller role in producing CO2 emissions compared to its counterparts among the top ten highest air polluters. This level suggests that the country is not considered a significant source of global air pollution, as its emissions are relatively lower in comparison to the other major contributors. The smaller the CI, the less the country impacts the overall pollution levels, making it a minor player in the global context of CO2 emissions.

These three categories allow for a clearer understanding of how individual countries within the highest pollution brackets contribute to global CO2 emissions, providing valuable insights for policymakers and researchers working to address climate change and air quality issues on a global scale.

Analysis of Determinants of Air Pollution Concentration
To analyze the determinants of air pollution concentration in this study, panel data regression is used. The panel data regression formula applied in this research is as follows:

$$\mathbf{Y = \beta 0 + \beta 1X1 + \beta 2X2 + \beta 3X3 + \text{c}it}$$

Description:
Y = Carbon Dioxide Emissions
β0 = Constant
X1 = Energy Consumption
X2 = Economic Growth
X3 = Population
B1,2, dan 3 = Regression coefficients of independent variables t = Year
i = Country
ε = Error term

In estimating the results of panel data regression, three approaches can be utilized: the Common Effect Model (CEM), the Fixed Effect Model (FEM), and the Random Effect Model (REM). To determine the best model for this study, three tests will be conducted: the Chow Test, the Hausman Test, and the Lagrange Multiplier Test.

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Once the appropriate model is identified for the panel data regression equation, classical assumption tests must be performed. If the chosen model is the FEM, it is sufficient to conduct only the multicollinearity and heteroscedasticity tests. Additionally, statistical tests such as the t-test, F-test, and goodness-of-fit test will also be carried out.

RESULTS

Air Pollution Concentration Analysis

The results of the concentration index analysis for the ten countries with the highest air pollution levels in the world from 2010 to 2020 indicate that the contribution of each country varies significantly.

Table 1. Concentration Index (CI) Air Pollution

No	Country	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	AVG
1	CHN	1.213	1.218	1.230	1.218	1.208	1.214	1.204	1.195	1.176	1.189	1.208	1.207
2	USA	1.293	1.291	1.283	1.274	1.278	1.286	1.257	1.241	1.231	1.226	1.231	1.263
3	IND	0.879	0.892	0.919	0.921	0.964	0.977	0.972	0.980	0.986	0.993	0.985	0.952
4	RUS	1.049	1.162	1.065	1.079	1.132	1.035	1.019	1.018	0.995	1.053	1.074	1.062
5	JPN	1.445	1.441	1.441	1.422	1.431	1.440	1.411	1.404	1.390	1.395	1.417	1.422
6	IDN	0.475	0.436	0.436	0.418	0.363	0.323	0.452	0.467	0.488	0.417	0.462	0.431
7	IRN	1.071	1.077	1.106	1.094	1.113	1.114	1.053	1.061	1.053	1.078	1.100	1.084
8	DEU	1.336	1.333	1.333	1.316	1.321	1.336	1.311	1.307	1.295	1.295	1.312	1.318
9	SAU	1.231	1.202	1.216	1.186	1.216	1.241	1.216	1.208	1.194	1.204	1.197	1.210
10	KOR	1.390	1.386	1.386	1.369	1.377	1.386	1.360	1.358	1.348	1.352	1.370	1.371

From Table 1, based on the average concentration index of air pollution during 2010-2020, eight out of ten of the world's most polluted countries fall into the category of having an air pollution concentration index greater than one (CI > 1). This indicates that these countries play a larger role in producing air pollution compared to others, making them the main contributors among the ten most polluted countries globally. Japan, South Korea, and Germany have the highest air pollution concentration levels due to their large manufacturing industries, which require substantial energy consumption. In Japan, following the Fukushima nuclear disaster in 2011, there was a sharp increase in dependence on fossil fuels due to the decline in nuclear energy. South Korea's industrial sector heavily relies on fossil energy to support its export-driven economy. Despite Germany's Energiewende policy, which promotes the use of renewable energy, the country continues to use coal, particularly lignite, which is highly polluting. As a result, these three countries have the highest air pollution concentrations.

Panel Data Regression Analysis

Out of the 195 countries worldwide, this study focuses on the ten countries with the highest air pollution levels based on carbon dioxide (CO2) emissions. Thus, the dataset consists of cross-sectional data for these 10 countries combined with time-series data for the years 2010-2020.

Model Selection Test

Based on the results of the model selection tests (Chow Test, Hausman Test), the FEM was determined to be the best model for analysis. The test results are as follows:

Table 2. Chow Test

Effects Test	Statistics	df	Prob.
Cross-section F	853.226293	(9.97)	0.0000
Cross-section Shi-square	482.250019	9	0.0000

From Table 2, the Chow test results show that the resulting probability of 0.0000 is smaller than the alpha of 0.05. This means that the FEM model is better.

Table 3. Hausman Test

Test Summary	Chi-Sq. Statistic	Chi-Sq. df	Prob.
Cross-section random	13.334079	3	0.0040

From Table 3, the Hausman Test results show that the probability value of 0.0040 is smaller than the alpha of 0.05. This indicates that the selected model is the FEM. Of the two test models, it shows that the selected model is the FEM, so there is no need to continue with the Langrange-Multiplier test.

Classical Assumption Test
Based on the Model Selection Test Results, it is found that the FEM is used as the best model. Therefore, the classical assumption test will only be carried out with multicollinearity and heteroscedasticity tests.

Multicollinearity Test
Table 4. Multicollinearity Test

	X1	X2	X3
X1	1	0.2642582972060867	0.6324695679688849
X2	0.2642582972060867	1	0.4909122351042922
X3	0.6324695679688849	0.4909122351042922	1

From Table 4, the multicollinearity test results show that the correlation coefficient on each variable is less than 0.8. This indicates that all variables are free from multicollinearity or pass the multicollinearity test.

Heteroscedasticity Test
Table 5. Heteroscedasticity Test

Dependent Variable: ABS(RESID)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	0.033392	0.036431	0.916576	0.3616
X1	1.72E-06	1.66E-06	1.036655	0.3025
X2	0.000710	0.000617	1.150308	0.2528
X3	-8.40E-11	1.13E-10	-0.746121	0.4574

The Heteroscedasticity Test in this study uses the Glejser Test. From Table 5, the probability value for each variable is more than alpha (0.05). This means that all variables in this study pass the heteroscedasticity test.

Statistical Test
Based on data processing, the results of Panel Data Regression with FEM method are shown in Table 6.

Table 6. Panel Data Regression Estimation Results with FEM

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	0.913438	0.065558	13.93336	0.0000
X1	-6.25E-06	2.99E-06	-2.090404	0.0392
X2	0.001130	0.001111	1.017500	0.3114
X3	7.21E-10	2.03E-10	3.559296	0.0006
Effects Specification				
R-squared	0.990101	Mean dependent var		1.131791
Adjusted R-squared	0.988877	S.D. dependent var		0.274033
S.E. of regression	0.028901	Akaike info criterion		-4.139262
Sum squared resid.	0.081023	Schwarz criterion		-3.820114

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Log-likelihood	240.6594	Hannan-Quinn criteria	-4.009814
F-statistic	808.5274	Durbin-Watson stat	1.288917
Prob (F-statisticc)	0.000000		

t-test
The t-test is used to determine the partial or individual impact of each independent variable on the dependent variable. Based on Table 6 with an alpha of 0.05, out of the three independent variables in the study model, two variables were found to significantly influence air pollution concentration: population and energy consumption. For the population variable (X3), at an alpha level of 0.05, the t-statistic value was 3.559296, which is greater than the t-table value of 1.65882, and the probability value was 0.0006, which is less than 0.05. This indicates that the population variable has a positive and significant effect on air pollution concentration. Meanwhile, for the energy consumption variable (X2, at an alpha of 0.05, the t-statistic value was -2.090404, which is less than the t-table value of -1.65882, with a probability value of 0.0392, which is also less than 0.05. This indicates that the energy consumption variable has a negative and significant effect on air pollution concentration. On the other hand, the economic growth variable showed a t-statistic value of 1.017500, which is less than the t-table value of 1.65882, and a probability value of 0.3114, which is greater than the alpha level of 0.05. This indicates that economic growth does not have a significant effect on air pollution concentration (CO_2 emissions) in the ten countries with the highest air pollution levels during 2010-2020.

F-test
The F-test is used to determine whether, simultaneously, all independent variables have a significant effect on the dependent variable. The data processing results show that the F-statistic value is 808.5274, which is greater than the F-table value of 2.69. This indicates that the variables of energy consumption, economic growth, and population collectively have a significant effect on air pollution in the ten countries with the highest air pollution levels worldwide during the period 2010-2020.

Goodness of Fit-Test
The Goodness of Fit test is used to assess the accuracy of the model as well as to determine how much the variation in the independent variables can explain the variation in the dependent variable. The Goodness of Fit test uses the coefficient of determination (R^2) value, which ranges between 0 and 1. Based on the test results, the Adjusted R-Squared value was 0.988877, meaning that variations in air pollution can be explained by the variables of energy consumption, economic growth, and population by 98.88%, while the remaining 1.12% is explained by other variables outside the model or study.

DISCUSSION

Based on the concentration index calculations, among the ten countries with the highest air pollution levels from 2010 to 2020, Japan, South Korea, and Germany emerged as the countries with the highest pollution concentration, with a CI value greater than 1. This indicates that these countries have a more significant role than others in generating air pollution and serve as the primary contributors to pollution among the ten most polluted countries worldwide.

The results show that population has a positive and significant impact on air pollution concentration. The population regression coefficient is 7.21E-10, meaning that for each additional person, air pollution concentration (CO_2 emissions) increases by 7.21E-10 points. This occurs as population growth raises transportation demand, leading to more vehicles and higher emissions. This finding aligns with Lawal and Abubakar (2019), who

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noted that population growth in Nigeria contributes to higher energy demand and fossil fuel consumption, increasing CO2 emissions. It also supports Assayuti et al. (2023), who found that higher population density is linked to more vehicle emissions and urban air pollution. However, Kirmanto et al. (2012) argue that developing eco-friendly infrastructure, improving waste management, and increasing urban greening are key to reducing pollution caused by population growth.

The energy consumption variable has a negative impact on air pollution concentration (CO2 emissions). The regression coefficient for energy consumption is - 6.25E-06, meaning that an increase of 1 terawatt-hour in energy consumption reduces air pollution (CO2 emissions) by 6.25E-06 points. Although the countries in this study are industrially advanced, their energy consumption reduces pollution due to their use of primary energy sources like solar, wind, water, geothermal, and unprocessed fossil fuels. Additionally, industrial, transportation, and other waste is often neutralized before being released, preventing further pollution. Fossil fuel energy, when burned, produces harmful emissions like CO2, SO2, and particulates that degrade air quality and human health, in line with Stern (2004) and Zhang et al. (2017). Reducing fossil fuel consumption and transitioning to clean energy are key to reducing air pollution and its health impacts (WHO, 2020).

The economic growth variable does not have a significant impact on air pollution concentration (CO2 emissions) in the ten countries with the highest air pollution levels from 2010 to 2020. This may be due to the implementation of eco-friendly policies and the use of clean technology in these countries. Several nations with high economic growth have adopted more efficient and environmentally friendly technologies, allowing them to sustain growth without deteriorating air quality. However, on the other hand, developing countries experiencing rapid economic growth still face severe pollution problems, as their growth often relies on heavy industries and fossil fuel-based energy.

CONCLUSION

Among the ten countries with the highest air pollution, eight have an air pollution concentration index greater than one, indicating their significant contribution to global pollution. These countries include Japan, South Korea, China, the United States, Russia, Iran, Germany, and Saudi Arabia. Japan, South Korea, and Germany have the highest pollution concentrations among these ten countries from 2010 to 2020.

Population has a positive and significant impact on air pollution, as a growing population increases the demand for energy for industrial activities, transportation, and other needs, resulting in higher pollution levels.

Energy consumption has a negative effect on air pollution, as the ten countries have shifted to primary energy sources like solar, wind, and geothermal, which are environmentally friendly and do not contribute to higher CO2 emissions.

Economic growth does not significantly affect air pollution, indicating that the countries in this study tend to use cleaner and more efficient technologies that do not increase CO2 emissions.

LIMITATION

This study has several limitations. First, this study only focuses on the ten countries with the highest air pollution levels, so the generalizability of the results to other countries may be limited. In addition, the methods used in examining the relationship between variables do not fully reflect the complexity of the relationship between these variables and air pollution concentrations. These limitations may provide direction for further research involving more countries and additional variables.

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DECLARATION OF CONFLICTING INTERESTS
The authors declare that there are no potential conflicts of interest related to this study, whether financial, professional, or personal that could influence the results and interpretations in this article.

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