연구논문 「환경정책」 제32권 특별호 2024. 6: 1-25
DOI http://dx.doi.org/10.15301/jepa.2024.32.S.1
pISSN 1598-835X eISSN 2714-0601

Transboundary Particulate Matter Pollution and the Environmental Kuznets Curve in Korea*

Tsurue Teshigawara** · Taeyean Yoon*** · Yuhyeon Bak**** · Yoon Lee*****

Abstract: Recent studies on the air pollution Environmental Kuznets Curve (EKC) in South Korea imply an N-shaped curve, suggesting the worsening of air pollution in the country. This study aims to test the EKC hypothesis of South Korea by considering China's transboundary air pollution effect. This paper estimates EKC for monthly PM_{10} with the generalized least squares approach using meteorological, local and economic factors, and China's effect during 2000-2021. The finding is that PM_{10} pollution shows an N-shaped trajectory EKC with turning points at $7,964 and $12,897, suggesting that PM_{10} increases as income increases since South Korea's GDP per capita has passed the second turning point and that China's effect may have played a role in the process of improving and deteriorating air quality in South Korea. The result also confirms that major air pollutants (PM_{10}, SO_2, and NO_2) are cointegrated using the seemingly unrelated regressions model. The findings suggest that the transboundary effects from neighboring countries should be considered when establishing policies to mitigate air pollution in South Korea.

Key Words: PM_{10}, Environmental Kuznets Curve, Fine dust, Air pollution, Transboundary

I. Introduction

Improving air quality in South Korea has long been a central issue for the government. The PM concentration of South Korea's capital, Seoul,

---

* This work was supported by the Ministry of Education of the Republic of Korea and the National Research Foundation of Korea.(NRF-2022S1A5C2A03093594).

** First Author, PhD. student, Department of Agricultural & Resource Economics, University of Connecticut

*** Coauthor, Associate Professor, Department of Global Economics, Sun Moon University

**** Corresponding Author, Research Professor, Global Sustainable Development Economics Institute, Sun Moon University

***** Coauthor, Associate Professor, Department of Global Economics, Sun Moon University

hit a concentration of 963㎍ m^{-3} in December 2009 and reached a staggering record of 1044㎍ m^{-3} in 2015 (Park, 2018). This is an alarming value considering the World Health Organization (WHO)'s air quality guideline value for PM_{10} which is set at 15㎍ m^{-3} for the annual mean and 45㎍ m^{-3} for the 24-hour mean. The government's stringent air quality regulations succeeded in decreasing the concentration levels of PM in the early 2000s (Song, 2019), but the fine dust concentration in South Korea still exceeds the WHO's air quality guidelines and remains at the bottom (35th out of 38 countries) among the Organization for Economic Co-operation and Development (OECD) member countries (Park, 2018).

Domestically, the Ministry of Environment recently implemented the Fourth Fine Dust Seasonal Management System in December 2022, with goals to reduce coal-fired power plant operations and abolish old power plants (Ministry of Environment, 2022). Attempts at international cooperation to mitigate air pollution have also been present. In August 2022, the Ministry of Environment and the Ministry of Ecology and Environment of the People's Republic of China jointly disclosed their plans to enhance international cooperation by continuously implementing the Korea-China Cheongcheon Plan and jointly publicizing the achievements of fine dust reduction between Korea and China (Ministry of Environment, 2022).

Regardless, it is evident that South Korea has yet to satisfy both national and international air quality guideline goals. Over the years, the environmental ramifications of the country's rapid economic growth have become an impetus for countless research and studies. The copious research includes studies on the environmental Kuznets curve (EKC) of a country, which looks at the relationship between economic growth and environmental degradation.

The EKC hypothesis proposed by Grossman and Krueger (1993) suggests an inverted U-shaped relationship between economic growth and environmental degradation. This means that as an economy starts moving along the growth trajectory, the environment first deteriorates due to pollution and other environmental consequences attributed to rapid industrialization, and then starts to improve when the economy starts to develop and reaches a particular income level. Unlike this hypothesis, recent research (Allard et al., 2018; Kang, 2019) suggests an N-shaped relationship between South Korea's environmental degradation and economic growth, with air pollution as the environmental indicator. This implies that although environmental degradation has been alleviated at some point, it has again started to rise. One plausible explanation for the rise of environmental degradation may be the transboundary factors, for example, that of the neighboring country China. Although empirical studies and reports (Ministry of Environment, 2017; Jia and Ku, 2019; Park et al., 2020) have long mentioned the effects of China's transboundary air pollutants on South Korea's air quality, there has not been any precedent research that has included China's effect to derive South Korea's EKC.

This paper attempts to answer the following question: What shape would South Korea's environmental Kuznets curve depict with China's transboundary air pollution effect? To answer this question, this study investigates the relationship between economic growth and South Korea's PM_{10} concentration and includes PM concentrations monitored at South Korea's coastal monitoring stations as a proxy variable of the China's effect.

This paper include two groups of control variables according to previous studies. The one is climate factors such as rainfall and westerly wind. Rainfall negatively affects the PM concentrations with removal of material from the atmoshphere by hydrometers (Yoo et al., 2020; Liu et al., 2020) and westerly wind intensifies transboundary transport effects (Chae, 2009; Sim, 2019; Jun and Gu, 2023). The other is local factors such as registered diesel vehicles in Seoul and diesel price in Seoul. The increase in diesel prices has the effect of reducing PM concentrations by decreasing diesel consumption (Lee, 2010; Bae and Kim, 2016; Cho 2020). The number of diesel vehicles has positive effect on the PM_{10} concentration (Kang, 2019).

This paper employs generalized least squares (GLS) to derive EKC and adopts seemingly unrelated regression (SUR) to visualize the relationship between PM and other major air pollutants in South Korea; sulfur dioxide (SO_2) and nitrogen dioxide (NO_2). The result shows an N-shaped trajectory EKC for South Korea's PM_{10} pollution with turning points at \$7,964 and \$12,897, implying that South Korea's per capita GDP has passed the second turning point and PM_{10} concentration increase as income increases. This paper further finds South Korea's major air pollutants are cointegrated.

The remainder of the paper is organized as follows. Section 2 introduce the relevant literature on EKC. Section 3 describes the data and empirical model. Section 4 provide the empirical results of the EKC analysis. Section 5 offers concluding remarks and corresponding implications.

II. Literature Review

Originated from Simon Kuznets (1985)'s proposal about an inverted

U-shaped relationship between inequality and economic growth, Grossman and Krueger (1993) found its resemblance with the relationship between a country's environmental degradation and economic growth. Since Grossman and Krueger (1993), a large body of research empirically investigates the validity of the EKC hypothesis for many environmental indicators such as suspended particles (Grossman and Krueger, 1993; Selden and Song, 1994), water pollutants (Grossman and Krueger, 1995; Cole, 2004), solid waste (Dinda, 2004; Diao et al., 2009), and deforestation (Cropper and Griffiths, 1994; Bhattarai and Hammig, 2001) using several explanatory variables such as trade (Grossman and Krueger, 1993; Shafik and Bandyopadhyay, 1992; Atici, 2012), energy consumption (Shafiei and Salim, 2014; Zhang et al., 2017), urbanization (Shafiei and Salim, 2014; Pata, 2018), and population density (Lantz and Feng, 2006; Salim et al., 2019).

For previous studies on South Korea's EKC, Cho et al. (2001), Choi and Kim (2006), Rhee (2016), and Dong et al. (2018) conduct multiple country analyses including South Korea and employ carbon dioxide (CO_2) as the common environmental indicator. However, the earlier single-country studies on EKC of South Korea use multiple air pollutants such as total suspended particulates (TSP), sulfur oxides (SO, SO_2), and nitrogen oxides (NO, NO_2). Kim and Oh (2005) compare the EKC shapes and patterns and Kim (1999) shows air and water pollutants together. Lee and Li (2009), Lee (2010), Bae and Kim (2012) and Park and Park (2019) examine the relationship between economic growth and CO_2 emissions. The findings of those studies show conflicting results for EKC's shapes and significance. Lee and Lee (1996), Kim et al. (1998) and Kim (2002) collected regional TSP data and found an inverted U-shaped EKC with turning points occurring at different economic levels.

With the start of the monitoring of PM_{10} in 1995, particulates in the air were separated from total suspended particulates. Kim and Kim (2008) and Yoon and Han (2010) explored South Korea's municipalities and economic regions using multiple air pollutants including PM_{10} and found both inverted U and U-shaped EKC relationships. Kang (2019) examined the EKC hypothesis for 16 economic regions in South Korea during the period 2003-2014 using gross regional domestic product (GRDP) as the economic indicator and PM_{10} as the environmental indicator, and showed an N-shaped relationship between air pollution caused by PM_{10} and economic development with the spatial Durbin model (SDM).

Table 1 summarizes prior literature for South Korea's EKC. In Table 1, turning points of South Korea's EKC happen faster for TSP than CO_2. A possible explanation for this result is that the government started taking measures to mitigate TSP before greenhouse gas emissions problems started to rise globally, explaining the early turning points for TSP than CO_2. Empirical evidence of the shape of South Korea's EKC in Table 1 is mixed and a plausible explanation is due to the possibility of transboundary factors.

Related with transboundary factor, Sim (2019) reported that long-range transboundary transport of air pollutants has also been affiliated with the PM_{10} concentration levels of South Korea. Several research showed that transboundary transport effects intensify under meteorological conditions such as westerly winds from China to Korea (Sim, 2019; Jun and Gu, 2023).

〈Table 1〉 The summary of EKC literature for South Korea

	Author(s)	Context	Pollutant	Explanatory Variables	Type of Data (Power of Income)	Methodology	Shape of EKC	Turning Point(s)
CO_2	Lee and Li (2009)	Seoul Metropolitan Area (1990~2007)	CO_2	Energy price, population density	Panel (Quadratic)	SUR	Inverted U	\$28,144~\$31,935
	Lee (2010)	3 Regions (1990–2007)	CO_2	Energy price, population density	Panel (Quadratic)	SUR	Inverted U	\$29,844~\$47,053
	Bae and Kim (2012)	156 Municipalities (2006)	GHG Emission	-	Cross-section (Quadratic)	3SLS	Inverted U	\$33,053
	Park and Park (2019)	South Korea (1971–2010)	CO_2	Total energy consumption, nuclear energy ratio, renewable energy ration, coal ratio, cooling and heating days	Time-series (Cubic)	FMOLS	Inverted U, N-shaped	\$31,183
TSP	Lee and Lee (1996)	Economic regions 1985–1992	SO_2,CO,NO_2,TSP,O_3,pH,BOD,COD,SS	GDP per capita	Time-series (Quadratic)	FE, RE GLS	Inverted U	\$3,554
	Kim et al. (1998)	Seoul Metropolitan Region (1980–1995)	SO_2,TSP,NO_2,CO	RGDP per capita	Panel (Quadratic)	RE GLS	Inverted U	\$15,249~\$17,427
	Kim (2002)	Seoul Metropolitan Region (1985–1999)	SPM, SO_2,NO_2,CO	GRDP per capita	Panel (Quadratic)	RCM	Inverted U	\$5,582
PM_{10}	Kim and Kim (2008)	31 Municipalities in Gyeonggi-do (1999–2004)	NO_x,SO_x,PM_{10}	GRDP per capita	Panel (Quadratic)	Two-way ECRM	Inverted U	-
	Yoon and Han (2010)	6 Economic Regions (1999–2005)	CO, SO_2,PM_{10},NO_2,O_3	GRDP per capita	Panel (Quadratic)	OLS	Inverted U, U-shaped	
	Kang (2019)	16 Economic Regions (2003–2014)	PM_{10}	GRDP, coal-fired power generation, number of diesel vehicles, yellow dust days, consumption of bituminous coal	Panel (Cubic)	SAR, SEM, SDM	N-shaped	-

Note: This table summarize previous studies on South Korea's ECK. Research in this table uses CO_2, TSP, and PM_{10} as environmental degradation indicators. The turning points are calculated in 2015 USD.

Studies on meteorologic factors affecting air pollutant concentration suggest that the rainfall and westerly wind have also been associated with the concentration levels of air pollutant. Chae (2009) investigated the relationship between wind speed and direction with PM10 concentrations and found that westerly wind passing through China's most industrially intense regions is associated with high concentration levels of PM10. Yoo et al. (2020) and Liu et al. (2020) found that rainfall negatively affects the PM concentrations due to the precipitation scavenging effect, which is the removal of material from the atmosphere by hydrometeors (Loosmore and Cederwall, 2004). The Korea Energy Economic Institute has also reported that days of rainfall affects the PM levels (Sim, 2019), in line with Yoo et al. (2020) and Liu et al. (2020). Related with local factors such as energy price and the number of registered vehicles, Lee (2010), Bae and Kim (2016) and Cho (2020) showed that increasing energy prices negatively affect air pollutant through the effect of curbing energy demand. Kang (2019) found that the number of registered diesel cars increases the PM10 concentration in the registered area.

Ⅲ. Data and Methodology

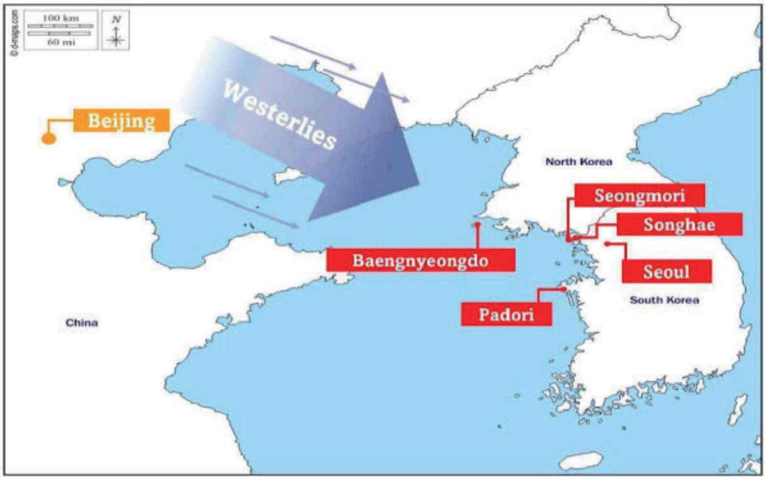
1. Data

In this paper, monthly time series data was used and spans from January 2000 to December 2021. This study takes the PM_{10} concentrations of Seoul as the dependent variable because Seoul has social significance and the results of the atmospheric diffusion model suggest that Seoul is affected by PM from China. Monthly average Seoul's PM_{10} concentration measured in μg m^{-3}, denoted by SeoulPM was retrieved from Air Korea website, which was launched by the Korean Ministry of Environment to provide air pollution information.

Economic growth variables and the transboundary factor were included as main explanatory variables in addition to weather and local factors. Following the traditional EKC literature, per capita GDP was used as the indicator for South Korea's economic growth (Shafik and Bandyopadhyay, 1992; Panayotou, 1993; Grossman and Krueger, 1995). Per capita GDP measured in 2015 US dollars, denoted by GDPPC, was retrieved from the OECD statistics database.

According to reports that long-range transboundary transport of air pollutants has also been affiliated with the PM_{10} concentration levels of South Korea, this paper employs China's transboundary air pollution effect as transboundary factor (Sim, 2019; Jun and Gu, 2023). As proxy of China's transboundary air pollution, the average PM_{10} concentration measured at the Seongmori, Padori, and Songhae monitoring stations, denoted by ChinaPM, is used. The data is measured in μg m^{-3} and is retrieved from the Air Korea website. The Baengnyeongdo air pollution monitoring station located in the middle of Korea and China is the most appropriate monitoring station to extract data from outside South Korea. Since there are no factories or much traffic on the Baengnyeongdo island, its monitoring station has been built and utilized to monitor international air pollution effects. However, unfortunately, it was only built in 2012, providing insufficient data for our analysis from 2000 to 2021. In place, the PM_{10} concentration monitored at the Seongmori, Padori, and Songhae is adopted in the analysis because these monitoring stations are all located on the Northwestern coastline of the South Korea as shown in figure 1.

〈Figure 1〉 Map of westerlies and coastal monitoring stations



Based on previous studies, the days of rainfall and days of westerlies are employed as weather factor, and the price of diesel and the ratio of registered diesel vehicles are adopted as local factor (Lee, 2010; Bae and Kim, 2016; Chae, 2009; Kang, 2019; Sim, 2019; Zhou et al., 2020; Yoo et al., 2020). The days of rainfall, denoted by Rainfall, refers to the number of days per month where the daily amount of precipitation was greater than or equal to 0.1mm in Seoul. The days of westerlies, denoted by Wind, refers to the number of days the westerly wind has been observed in Baengnyeongdo each month. Here, the westerly wind is defined as wind blowing from between 225~315° in a 16-wind direction geographic coordinate system, following the works of Kim et al. (2022). The data for rainfall and westerly wind are retrieved from the Korea Meteorological Administration database. The price of diesel, denoted by $Diesel_p$, refers to the average price of diesel in Seoul and is provided from Korea national oil corporation. The ratio of registered diesel vehicles, denoted by $Diesel_r$, is defined as the ratio of registered diesel cars to the total number of cars registered in Seoul. The data for registered vehicles is retrieved from Ministry of Land, Infrastructure and Transport.

To explore relationship between South Korea's main air pollutants using the SUR regression model, average SO_2 and NO_2 concentration of Seoul, denoted by $SeoulSO_2$ and $SeoulNO_2$, are used as other ambient air pollutants. Average SO_2 and NO_2 concentration of Seoul measured in 1000ppm were retrieved from Air Korea. Averages of SO_2 and NO_2 concentration monitored at Seongmori, Padori, and Songhae, denoted by $ChinaSO_2$ and $ChinaNO_2$, is the same mechanisms as ChinaPM.

The summary of the variable definition is presented in Table 2 and the descriptive statistics of the variables and the results of unit root test are displayed in Table 3.

〈Table 2〉 Variable definition

Variable Name	Unit	Description	Data Source
SeoulPM	$\mu g\ m^{-3}$	Average PM_{10} concentration of Seoul	Air Korea
GDPPC	1000 USD (2015)	South Korea's GDP per capita	OECD Statistics DB
Rainfall	Days	Number of days of rainfall in Seoul	Korea Meteorological Administration DB
Wind	Days	Number of days westerlies were monitored in Baengnyeongdo	Korea Meteorological Administration DB
$Diesel_r$	Percent	The ratio of registered diesel cars to the total number of cars registered in Seoul	Ministry of Land, Infrastructure and Transport
$Diesel_p$	won/liter	Average price of diesel in Seoul	Korea national oil corporation
ChinaPM	$\mu g\ m^{-3}$	Average PM_{10} concentration of Seongmori, Padori, and Songhae	Air Korea
$SeoulSO_2$	1000ppm	Average SO_2 concentration of Seoul	Air Korea
$SeoulNO_2$	1000ppm	Average NO_2concentration of Seoul	Air Korea
$ChinaSO_2$	1000ppm	Average SO_2 concentration of Seongmori, Padori, and Songhae	Air Korea
$ChinaNO_2$	1000ppm	Average NO_2 concentration of Seongmori, Padori, and Songhae	Air Korea

〈Table 3〉 Descriptive Statistics

Variables	Obs.	Mean	Std. Dev.	Min.	Max.	ADF
SeoulPM	264	52.17	18.98	15.00	147.00	−6.83***
GDPPC	264	11.13	2.09	7.33	14.46	−1.60*
Rainfall	264	9.17	4.39	0.00	25.00	−11.53***
Wind	257	12.16	6.34	1.00	27.00	−7.48***
$Diesel_r$	262	30.36	4.57	19	36.78	−6.95***
$Diesel_p$	264	1329.40	374.04	558.74	1977.28	−1.91**
ChinaPM	264	48.46	13.81	17.02	102.67	−8.24***
$SeoulSO_2$	264	5.52	1.58	2.42	10.50	−4.95***
$SeoulNO_2$	264	40.56	8.06	13.83	56.00	−5.34***
$ChinaSO_2$	264	3.23	1.05	1.05	8.20	−5.48***
$ChinaNO_2$	264	7.57	2.08	3.40	13.00	−7.44***

Note: SeoulPM and ChinaPM measured in $\mu g\ m^{-3}$; GDPPC measured in 1000USD; Rainfall and Wind measured in days; Diesel_r measured in percent; Diesel_p measured in won/liter; $SeoulSO_2$, $SeoulNO_2$, $ChinaSO_2$, $ChinaNO_2$ measured in 1000ppm. ADF is augmented Dickey-Fuller test statistics for unit root. Statistical significance at the 1, 5, 10 percent level is indicated by ***, **, and *, respectively.

2. Model specification

To examine validity and the shape of EKC relationship regarding South Korea's economic growth and PM_{10} pollution concentration, this study extends the existing EKC model by adding international transboundary factor of China's pollution effect, with climate and local factors including rainfall, wind, the ratio of registered diesel vehicles in Seoul and the price of diesel in Seoul (Chae, 2009; Lee, 2010; Bae and Kim, 2016; Kang, 2019; Sim, 2019; Cho 2020; Zhou et al., 2020; Yoo et al., 2020; Jun and Gu, 2023). Following the traditional environmental Kuznets curve equation, the empirical equation for South Korea's EKC is represented in a cubic form as follows:

$$SeoulPM_t = f(income,\ climate\ factors,\ local\ factors,\ transboundary\ factor) \quad (1)$$

$$SeoulPM_t = \beta_0 + \beta_1 GDPPC_t + \beta_2 GDPPC_t^2 + \beta_3 GDPPC_t^3 + \beta_4 Rainfall_t + \beta_5 Wind_t + \beta_6 Diesel_r + \beta_7 \log(Diesel_p) + \beta_8 ChinaPM_t + \epsilon_t \quad (2)$$

where SeoulPM represents the monthly PM_{10} concentration of Seoul, GDPPC denotes South Korea's GDP per capita, $GDPPC^2$ is the GDP per capita squared, $GDPPC^3$ is the GDP per capita cubed, Rainfall is the days of rainfall observed in Seoul, Wind is the days of westerlies observed in Baengnyeongdo, $Diesel_r$ is the ratio of registered diesel cars to the total number of registered cars in Seoul, $Diesel_p$ is the average price of diesel in Seoul, ChinaPM is the proxy for China's PM effect in South Korea, and ϵ is the error term. To search for a possible N-shaped trajectory, the cubic function was used in stead of the quadratic function and the EKC depicts an N-shaped relationship if the sign of β_1, β_2 and β_3 show an (+), (-), (+) pattern and ${\beta_2}^2 - 3\beta_1\beta_3$ is positive.

As mentioned in the Section 2, rainfall is expected to lessen the concentration of ambient air pollutants due to its precipitation scavenging effect. Therefore, it is expected that $\beta_4 < 0$. Since westerly wind monitored at the Baengnyeongdo island is being considered instead of the wind at Seoul, it is expected that the effect of westerly wind, or the more frequent westerly wind is observed in Baengnyeongdo, the higher the PM_{10} concentration of Seoul will be. Thus, it is expected that $\beta_5 > 0$. It is expected that $\beta_6 > 0$ because air pollutants increase as diesel vehicles increase. As diesel prices rise, diesel consumption decreases and air pollutants decrease accordingly. Thus, it is expected that $\beta_7 < 0$. Finally, since this research is based on the strong assumption that China's air pollution affects South Korea as a transboundary factor, it is expected that China's PM effect will have a positive effect on Seoul's PM_{10}, in other words $\beta_8 > 0$.

3. Modeling approach

This paper first derives the EKC for South Korea's PM_{10} concentration with and without China's effect in equation (2) using GLS regression. Derivation of the two shapes of EKC for South Korea's PM_{10} is performed to i) confirm the existence of the EKC relationship between environmental degradation and economic growth in the case of South Korea, and ii) compare the shape and turning points of the two EKCs to investigate China's air pollution effect on South Korea's EKC.

Second, this study examines the relationship between three ambient air pollutants, Seoul's PM_{10}, SO_2, and NO_2 concentrations, using the SUR estimation. The SUR is a system regression estimator which jointly estimates multiple models, allowing for a joint hypothesis testing of parameters a cross models since the parameter covariance is robust to the correlation of residuals across models. The SUR regression is estimated using equation (2) and the following equations:

$$\begin{aligned} SeoulSO_{2t} = {} & \beta_0 + \beta_1 GDPPC_t + \beta_2 GDPPC_t^2 + \beta_3 GDPPC_t^3 + \beta_4 Rainfall_t \\ & + \beta_5 Wind_t + \beta_6 Diesel_r + \beta_7 \log(Diesel_p) + \beta_8 ChinaSO_{2t} + \epsilon_t \end{aligned} \quad (3)$$

$$\begin{aligned} SeoulNO_{2t} = {} & \beta_0 + \beta_1 GDPPC_t + \beta_2 GDPPC_t^2 + \beta_3 GDPPC_t^3 + \beta_4 Rainfall_t \\ & + \beta_5 Wind_t + \beta_6 Diesel_r + \beta_7 \log(Diesel_p) + \beta_8 ChinaNO_{2t} + \epsilon_t \end{aligned} \quad (4)$$

with the only difference in the dependent variables and the China effect of the equations. The correlation of the residuals is calculated to visualize the relationship between the three pollutants.

Ⅳ. Results and Discussion

1. GLS Estimation Results

Table 4 shows the GLS estimation results for Seoul's PM_{10}. The sign of the GDPPC, its quadratic and cubic term for South Korea's EKC with China's PM effect depict an (+), (-), (+) pattern at significance levels 5% or higher and $\beta_2{}^2 - 3\beta_1\beta_3$ is positive. Thus, this result shows that South Korea's current EKC between PM_{10} and economic growth, with several factors including China's influence, depicts an N-shaped relationship. The sign of Wind is positive and this results are consistent with Chae (2009), Sim (2019), and Jun and Gu (2023).

ChinaPM has a positive influence on Seoul's PM_{10} concentration at a significance level of 1%. This result is a strongly support for our claim that China's transboundary air pollution effect has the rise of Seoul's air pollution. The sign of the GDPPC, its quadratic and cubic term for South Korea's EKC without China's PM effect show the same pattern of (+), (-), (+) and $\beta_2{}^2 - 3\beta_1\beta_3$ is positive, indicating an N-shaped EKC just like the case of EKC with China's effect. However, all coefficient except for $GDPPC^2$, Wind and price of diesel do not have a statistically significant effect on Seoul's PM_{10} concentration. Wind has a significantly negative effect and the price of diesel is positively effect on the concentration of ambient air pollution. Our findings suggest South Korea's EKC derives a significant N-shape trajectory EKC by adding China's effect.

〈Table 4〉 The effects of China's PM on South Korea's EKC

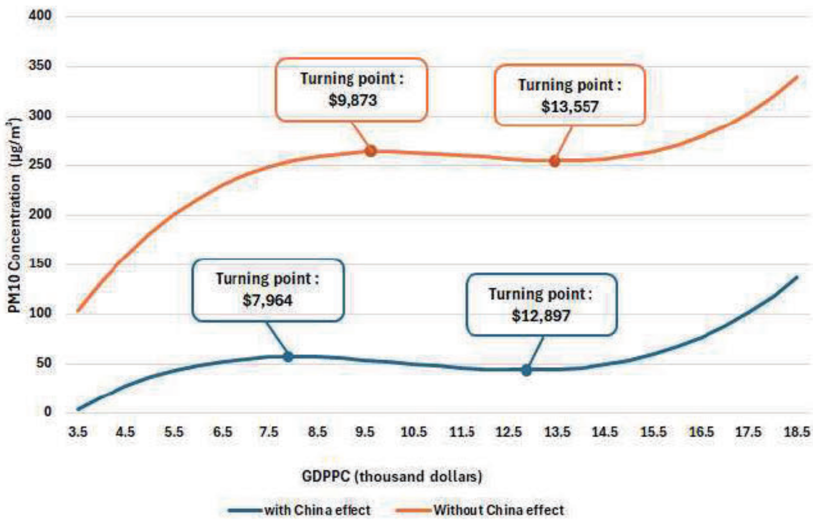
Variables	With China	Without China
Constant	-162.815 (-1.059)	-235.034 (-0.723)
GDPPC	69.59* (1.402)	133.384 (1.265)

$GDPPC^2$	-7.067** (-1.663)	-11.674* (-1.296)
$GDPPC^3$	0.226** (1.837)	0.332 (1.276)
Rainfall	-0.039 (-0.488)	-0.752 (-3.969)
Wind	0.134** (1.822)	0.579*** (3.357)
$Diesel_r$	0.316 (0.513)	-0.855 (-0.654)
$Diesel_p$	-8.447 (-1.104)	-25.242* (-1.526)
ChinaPM	1.082*** (33.837)	

Note: The dependent variable is PM_{10} concentration of Seoul. The column labelled as "WithChina" reports the results of EKC including China'sPM effect. The column labelled as "WithoutChina" reports the results of EKC except for China's PM. The numbers in parentheses are z-values. Statistical significance at the 1, 5 and 10 percent level is indicated by ***, **, * respectively.

Figure 2 plots the graph of both of the EKCs derived by the GLS analysis. For the EKC with the China effect, the first turning point occurred at $7,964 GDPPC, and the second at $12,897. The first turning point GDPPC value derived in this analysis is fairly close to the turning points derived in previous research on South Korea using TSP (Kim, 2002). However, the turning points of PM_{10} arrive at a much earlier point of economic development compared to the turning points of the EKC derived for South Korea's CO_2 (Lee and Li, 2009; Lee, 2010; Bae and Kim, 2012; Park and Park, 2019). The EKC for South Korea without the China's effect is drawn for visual comparison with the EKC with China effect, although estimates of per capita GDP for South Korea's EKC without China's effect are insignificant.

〈Figure 2〉 EKC with and Without China Effect



2. SUR Estimation Results

Table 5 shows the SUR estimation results for PM_{10}, SO_2, and NO_2. The coefficient values for the PM_{10} estimates in the SUR model are almost identical to the GLS estimation results in Table 4, with slight changes in the values of the coefficients.

The signs of the GDPPC, its quadratic and cubic term for dependent variable "SO_2" is the same as those for dependent variable "PM_{10}", showing a pattern of (+), (-), and (+), however, statistically insignificant. The Rainfall is significantly negative effect on SO_2 but the Wind is significantly positive effect on SO_2. This results suggest that Rainfall and Wind are both climate factors affecting ambient air pollution. Although the China's effect of SO_2 concentration is smaller than that of PM_{10} concentration, China's air pollution effect is also significantly visible in the case of SO_2.

On the other hand, in the case of NO_2, all the explanatory variables show a strong significance level except for the diesel price. The signs of the GDPPC, its quadratic and cubic terms show a (-), (+), (-) pattern, but $\beta_2{}^2 - 3\beta_1\beta_3$ is negative. This implies that NO_2 concentrations decreases as GDPPC increases. Besides the per capita GDP, the Rainfall has a significantly negative effect and the Wind has significantly positive effect, which is consistent with results of the other cases. Finally, China's NO_2 effect shows a significant positive value. In the SUR model, the China's effect of NO_2 had the greatest value among the three pollutants (1.513 〉 1.047 〉 0.698), suggesting that China's air pollution effects may have a greater impact on South Korea's NO_2 concentrations than PM_{10} concentrations.

The chi-square (χ^2) values were 2282.63 for PM_{10} concentration, 688.55 for SO_2, and 920.89 for NO_2 concentration, which were all significant at 1% significance level. Those values imply that the SUR model is able to explain a great proportion of the relationship between the variables.

〈Table 5〉 The effects of China's PM_{10}, SO_2, NO_2 on South Korea's EKC

Variables	PM_{10}	SO_2	NO_2
GDPPC	47.021* (1.77)	5.537 (1.50)	−52.028*** (−3.09)
$GDPPC^2$	−5.589** (−2.40)	−0.421 (−1.31)	4.928*** (3.34)
$GDPPC^3$	0.196*** (2.83)	0.009 (0.96)	−0.163*** (−3.73)
Rainfall	−0.073 (−0.75)	−0.067*** (−5.18)	−0.454*** (−7.42)
Wind	0.216*** (2.81)	0.016* (1.68)	0.088* (1.80)
$Diesel_r$	52.122 (1.33)	5.797 (1.09)	94.160*** (3.74)
$Diesel_p$	−0.001 (−0.30)	−0.001* (−1.84)	0.003 (1.52)

China	1.047*** (32.99)	0.698*** (12.25)	1.513*** (11.69)
R^2	0.898	0.719	0.783
χ^2	2282.63	688.55	920.89

Note: The column labelled as "PM_{10}" shows the estimation results including China's PM_{10} effect with PM_{10} concentration of Seoul as the dependent variables. The column labelled as "SO_2" shows the estimation results including China's SO_2 effect with SO_2 concentration of Seoul as the dependent variables. The column labelled as "NO_2" shows the estimation results including China's NO_2 effect with NO_2 concentration of Seoul as the dependent variables. Variable "China" measures China's PM_{10}, SO_2, and NO_2 in each column. The numbers in parentheses are z-values. Statistical significance at the 1, 5, 10 percent level is indicated by ***, **, * respectively.

The correlation matrix of the residuals from the SUR estimation is summarized in Table 6. The correlation coefficient of PM_{10} and SO_2 is valued at 0.304 and the correlation coefficient of PM_{10} and NO_2 was valued at 0.269, both showing a relatively weak correlation. The results also indicate that the NO_2 and SO_2 concentration has a stronger correlation, compared with that of PM_{10}, having a correlation coefficient of 0.371. The chi-squared value from the Breusch-Pagan test of independence was valued at 76.958 with a p-value less than 1% level of significance, indicating presence of heteroskedasticity in the regression model.

〈Table 6〉 Correlation matrix of residuals

	PM_{10}	SO_2	NO_2
PM_{10}	1.000	-	-
SO_2	0.304	1.000	-
NO_2	0.269	0.371	1.000

Note: Breusch-Pagan Test of Independence: = 76.958 ($p < 0.01$)

Ⅴ. Conclusion

Using monthly time-series monthly data covering from January 2000 to December 2021, this study attempts to investigate the effect of China's PM, an international transboundary factor on South Korea's air pollution within the framework of South Korea's environmental Kuznets curve (EKC). This paper contributes to previous literature in two ways; i) it attempts for the first time to use transboundary factors to derive South Korea's EKC for air pollution using the most recent data available and ii) that comprehensive national air pollution measures is considered

Including China's air pollution effect in South Korea's PM_{10} EKC derives an N-shaped trajectory EKC, with turning points first at $7,964 and then the second at $12,897 GDP per capita. This finding suggests that South Korea's per capita GDP has passed the second turning point and PM_{10} concentration increase as income increases. The result also shows that South Korea's EKC is statistically insignificant when China's effect is not considered. The finding implies that China's effect plays a role in the process of improving and deteriorating air quality in South Korea and that China's effect should be considered when suggesting the direction of the policy to mitigate air pollution.

Another important implication is that comprehensive national air pollution measures must be met in South Korea. The SUR analysis shows that PM_{10}, SO_2, and NO_2 are cointegrated, and are not completely independent. Therefore, comprehensive air quality improvement measures may be more effective measures that target single air pollutants.

This study only provides preliminary empirical evidence with limitations. First, given the lack of monthly data, some important indicators such as urbanization and population density were not considered in the study. Also due to the lack of data, proxy variables were composed and utilized in place of China's PM concentrations, and PM_{10} concentrations were used as environmental indicators instead of $PM_{2.5}$, which are pollutants considered to have greater health risks to humans. Therefore, adding an other indicator to the econometric model and exploring the socioeconomic drivers of PM_{10} emissions may lead to interesting results in future research. Second, as this study was the first attempt to include an international transboundary factor in the framework of EKC, the GLS model were used, ignoring some of the important aspects of air pollution considered in previous air pollution EKC studies, such as spatial autocorrelation and time lags.

▌References ▌

강희찬, 2019, "한국의 미세먼지 발생요인 분석: 공간계량모형의 적용," 『자원·환경경제연구』, 28(3), 327-354.

김정인·오경희, 2005, "한국의 환경쿠즈네츠 곡선에 관한 고찰," 『통계연구』, 10(1), 6-6.

김지욱·정의철·박상후, 1998, "수도권 환경오염과 지역경제발전에 관한 연구." 『아태경제학회 추계학술대회 논문집』, 57-85.

김지욱, 2002, "확률계수모형을 이용한 수도권지역의 환경쿠즈네츠가설에 관한 재고찰." 『자원·환경경제연구』, 11(3), 377-396.

김해동·김재혁·조하현, 2022, "패널 분위회귀분석을 통한 한국의 미세먼지 국내외 영향요인 분석." 『자원·환경경제연구』, 31(1), 85-112.

김지현·김미숙, 2008, "경기도 지역의 환경쿠즈네츠곡선 가설검증: 대기오염물질을 중심으로," 『환경논총』, 47, 141-155.

박세환, 2018, 『미세먼지 발생원인 및 대응정책 이슈』, 세종: 환경부; 서울: 한국환경산업기술원

박철웅·박철호, 2019, "한국의 탄소집약적 전원 믹스를 반영한 EKC (환경쿠즈네츠곡선) 가설의 검증," 『산업연구 (JIET)』, 3(2), 87-114.

배정환·김미숙, 2012, "생산함수 접근법을 이용한 온실가스 배출 결정요인 분석," 『응용경제』, 14(3), 107-132.

배정환·김유선, 2016, "우리나라 대기오염배출 원인과 저감 정책 효과 분석," 『자원·환

경경제연구』, 25(4), 545-564.

송창근, 2019, "미세먼지 현황과 대기질 예보." 에너지포커스, 2019봄, 6-11.

심창섭, 2019, "미세먼지의 주요원인과 대응 전략," 에너지포커스, 2019봄, 12-16.

유혁균·홍제우·홍진규·성선용·윤은주·박진한·이진홍, 2020, "기상 조건이 서울의 $PM_{2.5}$ 와 PM_{10} 에 미치는 영향," 『한국기후변화학회지』, 11(5-2), 521-528.

윤인주·한상연, 2010, "우리나라 대도시의 총생산과 환경오염의 관계에 관한 실증연구: 환경쿠즈네츠 곡선의 활용," 『한국정책연구』,10(1), 249-263.

이광수·이민원, 1996, "환경을 고려한 지역경제의 성장평가," 『자원·환경경제연구』, 5(1), 143-188.

이광훈·이춘화, 2009, "수도권 지역 이산화탄소 배출에 대한 환경 쿠즈네츠 곡선 탐색 및 정책적 함의," 『서울도시연구』, 10(3), 83-95.

이광훈, 2010, "국내 지역별 이산화탄소 배출에 대한 환경 쿠즈네츠 곡선 추정 및 비교," 『환경정책연구』, 9, 53-76.

이현재, 2016, "한중일 3 국간 상호무역에 의한 환경오염 배출 전가효과 분석," 『무역연구』, 12(2), 149-165.

조상섭·강신원·김동엽, 2001, "비정태적 패널자료를 이용한 환경 쿠즈네츠가설에 대한 실증분석-OECD 17 개국 사례분석," 『자원·환경경제연구』, 10(4), 619-632.

조향숙, 2020, "공간패널모형을 이용한 대기오염물질과 지역소득간 탈동조화 분석,"『환경정책』, 28(4), 1-32.

채희정, 2009, "풍속과 풍향이 미세먼지농도에 미치는 영향," 『환경위생공학』, 24(3), 28-45.

최충익·김지현, 2006, "경제성장과 환경오염간의 관계에 대한 국제비교연구: CO_2 의 환경쿠즈네츠곡선 검증을 중심으로,"『국토계획』, 41(1), 153-166.

Allard, A., Takman, J., Uddin, G. S., and Ahmed, A., 2018, "The N-shaped environmental Kuznets curve: an empirical evaluation using a panel quantile regression approach," *Environmental Science and Pollution Research*, 25, 5848-5861.

Atici, C., 2012, "Carbon emissions, trade liberalization, and the Japan-ASEAN interaction: A group-wise examination," *Journal of the Japanese and International Economies*, 26(1), 167-178.

Bhattarai, M., and Hammig, M., 2001, "Institutions and the environmental Kuznets curve for deforestation: a cross country analysis for Latin America, Africa and Asia," *World development*, 29(6), 995-1010.

Cole, M. A., 2004, "Trade, the pollution haven hypothesis and the environmental Kuznets curve: examining the linkages," *Ecological economics*, 48(1), 71-81.

Cropper, M., and Griffiths, C., 1994, "The interaction of population growth and environmental quality," *The American Economic Review*, 84(2), 250-254.

Diao, X. D., Zeng, S. X., Tam, C. M., and Tam, V. W., 2009, "EKC analysis for studying economic growth and environmental quality: a case study in China," *Journal of Cleaner Production*, 17(5), 541-548.

Dinda, S., 2004, "Environmental Kuznets curve hypothesis: a survey," *Ecological economics*, 49(4), 431-455.

Dong, K., Sun, R., Li, H., and Liao, H., 2018, "Does natural gas consumption mitigate CO2 emissions: testing the environmental Kuznets curve hypothesis for 14 Asia-Pacific countries," *Renewable and Sustainable Energy Reviews*, 94, 419-429.

Grossman, G. M., and Krueger, A. B., 1993, "Environmental Impacts of a North American Free Trade Agreement," *The Mexico-US Free Trade Agreement*, 11(2), 13.

Grossman, G. M., and Krueger, A. B., 1995, "Economic growth and the environment," *The quarterly journal of economics*, 110(2), 353-377.

Jia, R., and Ku, H., 2019,. "Is China's pollution the culprit for the choking of South Korea? Evidence from the Asian dust," *The Economic Journal*, 129(624), 3154-3188.

Jun, M. J., and Gu, Y, 2023, "Effects of transboundary $PM_{2.5}$ transported from China on the regional $PM_{2.5}$ concentrations in South Korea: A spatial panel-data analysis," *Plos one*, 18(4), e0281988.

Kim, J. H., 1999, "Does an Environmental Kuznets Curve Exist in Koreas Case?," *Journal of Environmental Policy and Administration*, 7(1), 169-191.

Kuznets, S., 1985, "Economic growth and income inequality," *The gap between rich and poor* (pp. 25-37). Routledge.

Lantz, V., and Feng, Q., 2006. "Assessing income, population, and technology impacts on CO2 emissions in Canada: where's the EKC?," *Ecological Economics*, 57(2), 229-238.

Liu, Z., Shen, L., Yan, C., Du, J., Li, Y., and Zhao, H., 2020, "Analysis of the Influence of Precipitation and Wind on $PM_{2.5}$ and PM_{10} in the Atmosphere," *Advances in Meteorology*, 2020, 1-13.

Loosmore, G. A., and Cederwall, R. T., 2004, "Precipitation scavenging of atmospheric aerosols for emergency response applications: testing an updated model with new real-time data," *Atmospheric Environment*, 38(7), 993-1003.

Park, H., Lim, W., and Oh, H., 2020, "Cross-border spillover effect of particulate matter pollution between China and Korea," *Korean Economic Review*, 36(1), 227-248.

Panayotou, T., 1993, "Empirical tests and policy analysis of environmental degradation at different stages of economic development. World Employment Programme Research," *International Labour Office, Geneva*.

Pata, U. K. 2018, "Renewable energy consumption, urbanization, financial development, income and CO_2 emissions in Turkey: testing EKC hypothesis with structural breaks," *Journal of cleaner production*, 187, 770-779.

Salim, R., Rafiq, S., Shafiei, S., and Yao, Y., 2019, "Does urbanization increase pollutant emission and energy intensity? Evidence from some Asian developing economies," *Applied economics*, 51(36), 4008-4024.

Selden, T. M., and Song, D., 1994, "Environmental quality and development: is there a Kuznets curve for air pollution emissions?," *Journal of Environmental Economics and management*, 27(2), 147-162.

Shafiei, S., and Salim, R. A., 2014, "Non-renewable and renewable energy consumption and CO2 emissions in OECD countries: a comparative analysis," *Energy policy*, 66, 547-556.

Shafik, N., and Bandyopadhyay, S., 1992, "Economic growth and environmental quality: time-series and cross-country evidence(Vol. 904)," *World Bank Publications*.

Zhang, B., Wang, B., and Wang, Z, 2017, "Role of renewable energy and non-renewable energy consumption on EKC: evidence from Pakistan," *Journal of cleaner production*, 156, 855-864.

Zhou, Y., Yue, Y., Bai, Y., and Zhang, L., 2020, "Effects of Rainfall on $PM_{2.5}$ and PM_{10} in the Middle Reaches of the Yangtze River," *Advances in Meteorology*, *2020*.

환경부, 2017, 미세먼지관리 종합대책, https://www.me.go.kr/home/web/policy_data/read.do?menuId=10262&seq=7053

환경부, 2022, 제4차 미세먼지 계절관리제 시행계획, https://www.me.go.kr/home/web/policy_data/read.do?menuId=10262&seq=7992

환경부, 2022, 한·중 환경당국, 초미세먼지 대응 현황 합동 공개, https://me.go.kr/home/web/board/read.do;jsessionid=-+v6DPvZws2Clbe11LW-wJB2.mehome1?pagerOffset=570&maxPageItems=10&maxIndexPages=10&searchKey=&searchValue=&menuId=10525&orgCd=&boardId=1541620&boardMasterId=1&boardCategoryId=39&decorator=

Tsurue Teshigawara: She received a master's degree in economics from the department of Global Economics in Sun Moon University and is a PhD. student in the department of agricultural and resource economics from University of Connecticut. Her fields of interest include sustainable development, environmental health, environmental development cooperation(tsurue.teshigawara@uconn.edu).

Taeyean Yoon: He received bachelor's and master's degree from Seoul National University and a PhD. from University of Connecticut. He is an associate professor at the department of Global Economics in Sun Moon University. His research fields include environmental topics such as fine dust and green alga as well as energy topics such as electricity bill and energy welfare (tay07001@sunmoon.ac.kr).

Yuhyeon Bak: She received a PhD. in economics from Korea University and is a research professor at the Global Sustainable Development Economic Institute in Sun Moon University. Her research interests include financial economics, green finance and environmental economics(yhbak208@sunmoon.ac.kr).

Yoon Lee: He received a PhD. in applied and resource economics from University of Connecticut and is an associate professor at the department of Global Economics in Sun Moon University. The main research fields are sustainable development, climate change, energy and water resource economics, and he has published a number of papers as the head of the Humanities and Social Sciences Research Institute(lyoon21@sunmoon.ac.kr).

Received: 25 January 2024
Revised: 31 May 2024
Accepted: 12 June 2024