# $PM_{2.5}$ Health Impacts in India due to International Trade in 2014

By

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# Abstract

Long-term exposure to $PM_{2.5}$ increases the relative risk of four chronic diseases — ischemic heart disease (IHD), stroke, chronic obstructive pulmonary disease (COPD), and lung cancer (LC), leading to premature death in the population. This study analyzed the increase in $PM_{2.5}$-related risks and the increase in the number of premature deaths caused by the consumption of Indian products worldwide in 2014. This work uses a multi-regional input-output (MRIO) method to analyze the impact of consumption on $PM_{2.5}$ emissions. IER health risk model is used to calculate the premature death caused by the four diseases caused by this part of the discharge. The study found that of the 6,200 Gg $PM_{2.5}$ emissions produced by India throughout the year, 49% came from trade, and 12% of that is international trade. India's annual $PM_{2.5}$-related premature death toll was 780,000, and international trade-related premature deaths were 94,000, of which IHD, stroke, COPD, and LC accounted for 44.6%, 34.7%, 14.2%, and 1.5%, respectively. The United States, China, and Germany are the most important countries and are responsible for 25% of the total premature deaths. Services and dwelling are the main causes of premature deaths in India, which account for 49% of the total deaths. This study puts forward that consumer groups in international trade should take responsibility for the pollution and health impacts of the product-producing country, and help the country that produces the product to control pollution emissions to achieve sustainable production and consumption.

# Acknowledgement

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# Table of Contents

# 1. Introduction

Particulate matter is a mixture of solid particles and liquid droplets. The US health standard for ambient air defined PM10 as including particles with an aerodynamic diameter of fewer than 10 microns. Fine-particle air pollution comprises particles with an aerodynamic diameter of 2.5 microns or less (Dockery et al., 1993). PM2.5 may cause several severe respiratory diseases since the human body cannot filter fine particles. Fine particulate matters contain various substances harmful to the human body, such as cyclic aromatic hydrocarbons, polycyclic benzene, bacteria, or other toxic substances (Xie et al., 2015). Studies suggested that PM2.5 exposure is related to four major diseases of adults and premature death of children (Brook et al., 2010; Gao et al., 2018). Anthropogenic activities, including industry, transportation, power generation, and residential energy use (heating and cooking), directly or indirectly lead to PM2.5 emissions through the conversion of gas to particles. There have been concerns about airborne pollution, but this is usually related to specific occupational or environmental conditions, such as lung disease in mining workers and the concentration of silica (Gao et al., 2018). These effects are more pronounced in countries with more populations, such as India, because more people are directly exposed to PM2.5 (Upandhyay et al., 2018). In recent years, research on PM2.5 is receiving more attention in many countries.

The population of India has increased dramatically in recent decades. In 1960, India had a population of about 450 million. By 2019, India's population has grown to 1.36 billion (Worldometer, 2020). It is one of the fastest-growing countries and will soon surpass China to become the most populous country in the world. The rapid population growth and industrialization have led to increasing demand for materials and energy. Due to internationalization, trade between countries has become more frequent. Today, India is heavily dependent on exports. The contribution of India's total import and export trade to gross domestic product (GDP) increased from 15.5% in 1990 to 43.1% in 2018 (United Nations, 2020). The total PM2.5 emissions increased from 3373.46 Gigagram in 1990 to 6154.21 Gigagram in 2015, which is almost doubled (EDGAR, 2020). International trade is shifting pollution emissions from developed countries to developing countries (Andrew and Peters, 2013). The global average annual total exposure of PM2.5 emissions increased from 44.3 micrograms per cubic meter in 1990 to 45.5 micrograms per cubic meter in 2017, and the change is not apparent. Meanwhile, the average annual exposure of PM2.5 in India has increased from 81.3 micrograms per cubic meter in 1990 to 90.9 micrograms per cubic meter, an increase of 12%, which is twice exposure level compared to the global PM2.5 exposure (The World Bank, 2017).

The rapid increase in PM2.5 exposure level has caused many problems. Lim et al. (2012) estimated that ambient PM2.5 pollution is the 5th most significant contributor to deaths in India. Lim et al. (2012) estimated that about 600,000 premature deaths in India caused by PM2.5 exposure each year. Zhang et al. (2015) pointed out that of the 3.45 million premature deaths related to PM2.5 worldwide in 2007, 22% were related to services and goods produced in one region and consumed in another. The impact of PM2.5 pollution related to international trade on health is more significant than the impact of air pollution transmission (Zhang et al., 2017). The analysis of the impact of international trade can help track drives of air pollution, and can also provide policymakers with considerations for industrial relocation or upgrade to more effectively reduce health risks.

In order to help solve India's health problems caused by PM2.5, it is essential to understand the details of emissions caused by global consumption facilitated by international trade. This study analyzes the PM2.5 emissions in India driven by global consumption as well as the associated health impacts. Due to the transfer of pollution from developed countries to developing countries, this thesis analyzes how much the various consumer sectors of different countries should be responsible for the premature death of the Indian population. This research can help better understand the link between air pollution and international trade. The result calls on developed countries to help developing countries in environmental protection for global sustainable development.

# 2. Literature review

## 2.1 Consumption-based emission analysis

Input-output analysis (IOA) is an ideal method for supply chain analysis and determining the relationship between production and consumption sectors (Leontief, 1986). This approach can extend to multi-regional input analysis (MRIOA) to analyze the global supply chain. For the rise of computable general equilibrium modeling (CGE) in economic analysis, the use of IOA methods for analysis has gradually decreased. However, more and more research in the field of environment began to use MRIOA for quantitative analysis (Minx et al., 2009; Wiedmann, 2009). Production-based accounting and consumption-based accounting are the two main methods in MRIOA (Wiedmann, 2009). Production-based accounting is similar to land-based accounting that they all rule that the countries which produce the products are responsible for pollution. Consumption-based accounting assigns the corresponding responsibility for export-related emissions to the importing country. In this way, the source of pollution can be accessed through a complex supply chain (Yang et al., 2018).

The MRIO method allocates the emissions reflected in the realization of intermediate consumption to the consumption region (Liu and Wang, 2017). Zhang combines four global models to predict premature death caused by PM2.5, and the result specifies the impact of PM2.5 pollution related to international trade on transboundary health is more significant than that related to long-distance air pollutant transportation (Zhang et al., 2017). Both global exports and inter-provincial trade have more health burden of air pollution in underdeveloped regions (Wang et al., 2017). In another research, 56% of the premature deaths related to PM2.5 in China are linked to consumption in another region, including 423,800 (42% of the total) premature deaths from domestic consumption and 145,100 (14%) of international trade respectively (Zhao et al., 2017). In general, consumption-based accounting is used more and more in research based on pollution transmission and health risks.

## 2.2 Premature death caused by $PM_{2.5}$

Pollution is the biggest environmental cause of disease and premature death in the world today. Diseases caused by pollution led to an estimated 9 million premature deaths in 2015, accounting for 16% of total deaths worldwide (Landrigan et al., 2018). However, despite its harmful effects on human health, economy, and the environment, and despite clear evidence that it can be controlled cost-effectively, pollution has been largely ignored, especially in developing countries (Greenberg et al., 2016). India, with a population of more than 1.3 billion, has been recognized as a regional pollution hotspot because the aerosol burden in this region continually remains high (Dey and Girolamo, 2010). There have been many articles analyzing the health effects of PM2.5 and pollution transfer through international trade. Burnett (2014) established an integrated exposure-response (IER) model in 2014. The model can combine information on relative risks

(RR) with PM2.5 pollution and evaluate four chronic diseases and premature death effects caused by PM2.5 exposure. Compared with the concentration-response model, mostly used in previous studies, the analysis of the IER model improves the accuracy of predicting specific types of RR. Chowdhury et al. (2016) used the NLP (IER) risk function and estimate 54.5% of premature deaths attributable to chronic obstructive pulmonary disease (COPD), 24.0% to ischemic heart disease (IHD), 18.5% to stroke, and the remaining 3.0% to lung cancer (LC) in India.

Combining health effects with input-output analysis can quantitatively analyze the health effects of various industrial sectors in different countries on other regions. Liang et al. (2017) find that the United States, Japan, and Germany have transferred 14% of their health effects to China and India through international trade. Although the impact of detailed industrial classifications on other regions is still uncertain, combining the IOA and IER methods can get the impression of major industrial classifications, which has a positive effect on environmental protection-related policy formulation.

### 2.3 General challenges and limitations

In the current research, there are several challenges in dealing with pollution lists and input-output tables. The pollution list used in this research is EDGAR 5.0, and the input-output table is GTAP 10. There is a difference between the product categories selected by GTAP and EDGAR. As an environmental emission inventory, EDGAR's classification standards are based on the IPCC 2006 code, and the number of sectors in different countries is different. The sector classification of GTAP10 is formulated according to economic standards, including a total of 65 sectors in each country. Therefore, it is necessary to correspond to the classifications and to analyze the overlapping classifications separately.

There is a large lag in the update of the data of this type of research. The EDGAR 5.0 used in this article is updated in April 2020, but the pollution information contained in it has only been updated to 2015. Therefore, the difficulty of data acquisition affects researchers’ analysis of pollution over the past few years. The input-output table differs in coverage countries and classification types, and there is a time lag in the update time. The GTAP 10 selected in this article covers 141 countries, and the product classification is relatively large, so detailed research can be carried out. Another mainstream input-output tables used in research such as WIOD and EORA cover fewer countries and are less specific in type. At the same time, there are still limitations on data accuracy in the analysis of input and output. The input-output table data is obtained from independent statistics of various countries. For some smaller countries or economies, it is relatively difficult to obtain a complete MRIO table, and the types and standards of products counted by countries are different. Therefore, there may be systematic errors in the analysis using the current types of input-output tables.

# 3. Methods

## 3.1 Multi-regional Input-Output (MRIO) method

The input-output model has been proven to be a useful top-down approach, which can allocate emissions according to demand through a consistent framework (Yang et al., 2016). In the MRIO framework, we introduce the technical coefficient matrix **A**, where $A^{ij} = Z^{ij}/X^{j}$. *i* is the sector of the producer sector, *j* is the sector of the consumer sector, and $Z^{ij}$ represents the money of trade from sector *i* to sector *j*.

The technical coefficient matrix is $\mathbf{A} = \begin{bmatrix} A^{11} & A^{12} & \dots & A^{1N} \\ A^{21} & A^{22} & \dots & A^{2N} \\ \vdots & \vdots & \ddots & \vdots \\ A^{N1} & A^{N2} & \dots & A^{NN} \end{bmatrix}$;

The final demand matrix is $\mathbf{Y} = \begin{bmatrix} y^{11} & y^{12} & \dots & y^{1M} \\ y^{21} & y^{22} & \dots & y^{2M} \\ \vdots & \vdots & \ddots & \vdots \\ y^{N1} & y^{N2} & \dots & y^{NM} \end{bmatrix}$;

The total output matrix is $\mathbf{X} = \begin{bmatrix} x^{1} \\ x^{2} \\ \vdots \\ x^{N} \end{bmatrix}$.

In the equations, $N$ is the total number of countries and $M$ is the total number of final demand categories.

According to the IO table, there exists a balance between the total output **X** and the final demand **Y.**

$$\mathbf{X} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y}.$$

where $(\boldsymbol{I} - \boldsymbol{A})^{-1}$ is the Leontief inverse matrix (Leontief, 1986). It reflects the direct and indirect impact of one unit's final demand on output (Miller & Blair, 2009) . **I** is an identity matrix, where one on the main diagonal and zero in other places.

## 3.2 The Integrated Exposure Response (IER) model

The IER model developed by Burnett et al. (2014) was used to describe the concentration-response relationship between exposure to $PM_{2.5}$ and premature death caused by several chronic diseases. The relative risk (RR) was calculated as:

$$\mathrm{RR}_l(C) = \begin{cases} 1 + \alpha_l(1 - e^{-\gamma_l (C - C_0)^{\delta_l}}), if\ C > C_0, \\ 1 \qquad\qquad\qquad\qquad\qquad , else \end{cases}$$

where C is the $PM_{2.5}$ in micrograms per meter cubed; $C_0$ is the counterfactual concentration; l is a given category of health effect; and $\alpha_l$ , $\gamma_l$ , and $\delta_l$ are parameters used to describe the shape of the concentration-response curve.

The RR was then converted to the attributable fraction (AF):

$$\mathrm{AF} = \frac{RR-1}{RR}. \qquad (2)$$

The health outcomes or mortality attributable to $PM_{2.5}$ was then estimated:

$$\mathrm{M} = \mathrm{AF} \times \mathrm{B} \times \mathrm{P}, \qquad (3)$$

where B is the basic death incidence of a given health effect derived from the national average data in GBD2013; P is the population cell given by the SEDAC, and the pixel is 1 km × 1 km.

This research mainly focuses on four leading causes of the $PM_{2.5}$-related premature deaths: ischemic heart disease (IHD), stroke, chronic obstructive pulmonary disease (COPD), and lung cancer (LC). They are proved directly impacted by $PM_{2.5}$. Theoretically, the minimum risk exposure concentration is reported to be in the range of 5.8 to 8.8 μg / $m^3$. In this study, based on research by Apte et al. (2015) and Maji et al. (2018), $C_0$ is assumed to be around 5.8 μg / $m^3$. α , γ , and δ are chosen from the result by the Global Burden of Disease (GBD) Study 2010. They use the nonlinear regression method, and the result has 1000 sets of parameters with each disease. The premature mortality rate is expressed as a 95% confidential interval (CI).

# 4. Result

## 4.1 Trade and others $PM_{2.5}$

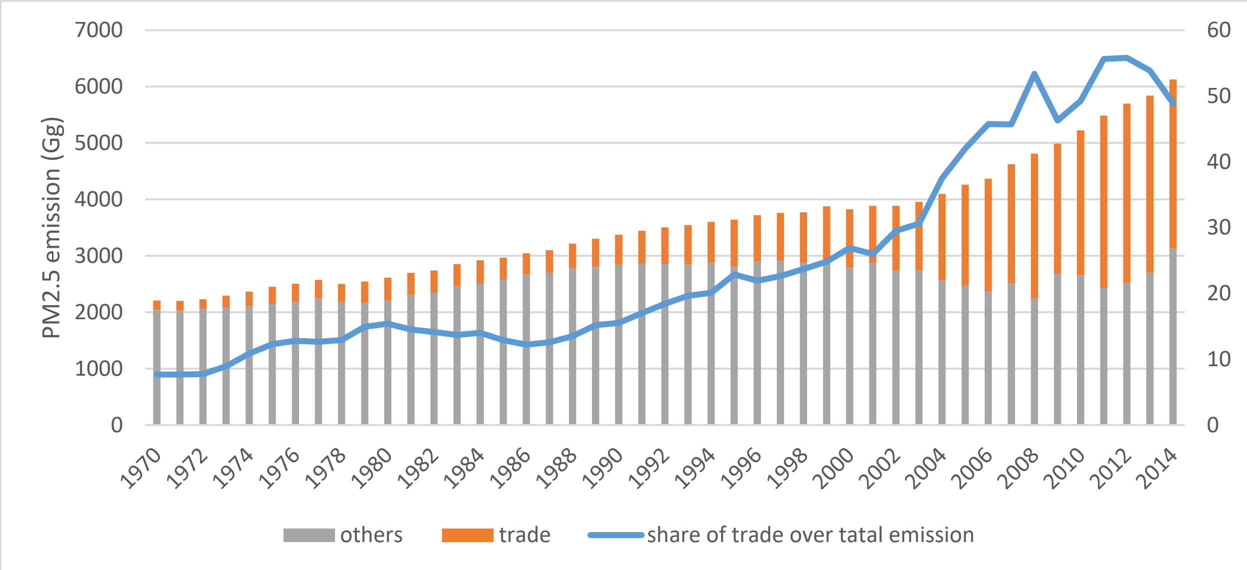


**Figure 1. Indian $PM_{2.5}$ emission by domestic and international trade**

The analysis of overall PM2.5 emissions in India could help to understand the contribution of international trade. From Figure 1, we can see that India's PM2.5 emissions have steadily increased year by year, from 2,208 Gg in 1970 to 6,126 Gg in 2014, an increase of 277%. Among them, India's other categories PM2.5 emission increase from 2,039 Gg in 1970 to 3,129 Gg. The emissions caused by trade increased from 169 Gg to 2,997 Gg, the proportion of total emissions increased from 7% to the highest 54% in 2012, and fell to 49% in 2014. International trade is the primary attribution of the increase in PM2.5 emissions in India, and it is becoming a major factor influencing population health problems.

The average annual exposure concentration of PM2.5 in India is in Figure 2. The data comes from SEDAC 2014. From this figure, we are able to analyze the main areas of long-term high concentration exposure of PM2.5 in India. The concentration of PM2.5 was classified according to the standard of PM2.5 used in Chowdhury et al. (2016), which was divided into eight levels: no impact, very low, low, moderate, high, very high, severe, and extreme. The higher the concentration of PM2.5 long-term exposure, the more significant the disease impact. The areas with medium and high levels of pollution in India are mainly in the northeast of the country.

Among them, the heavy pollution is concentrated in four regions: NCT of Delhi, Uttar Pradesh, Bihar and Haryana, most of which are covered by severe, and the exposure level of the central area reaches the extreme level. This is mainly due to the fact that the distribution of PM2.5 emission areas (Appendix Figure A) is concentrated in these three provinces and regions. Compared with the population distribution (Appendix Figure B), this is also the main population concentration area in India. Therefore, PM2.5 produced by living activities is one of the main reasons for the high PM2.5 concentration in the region. At the same time, it leads to more people exposed to high levels of PM2.5, which leads to more premature deaths.

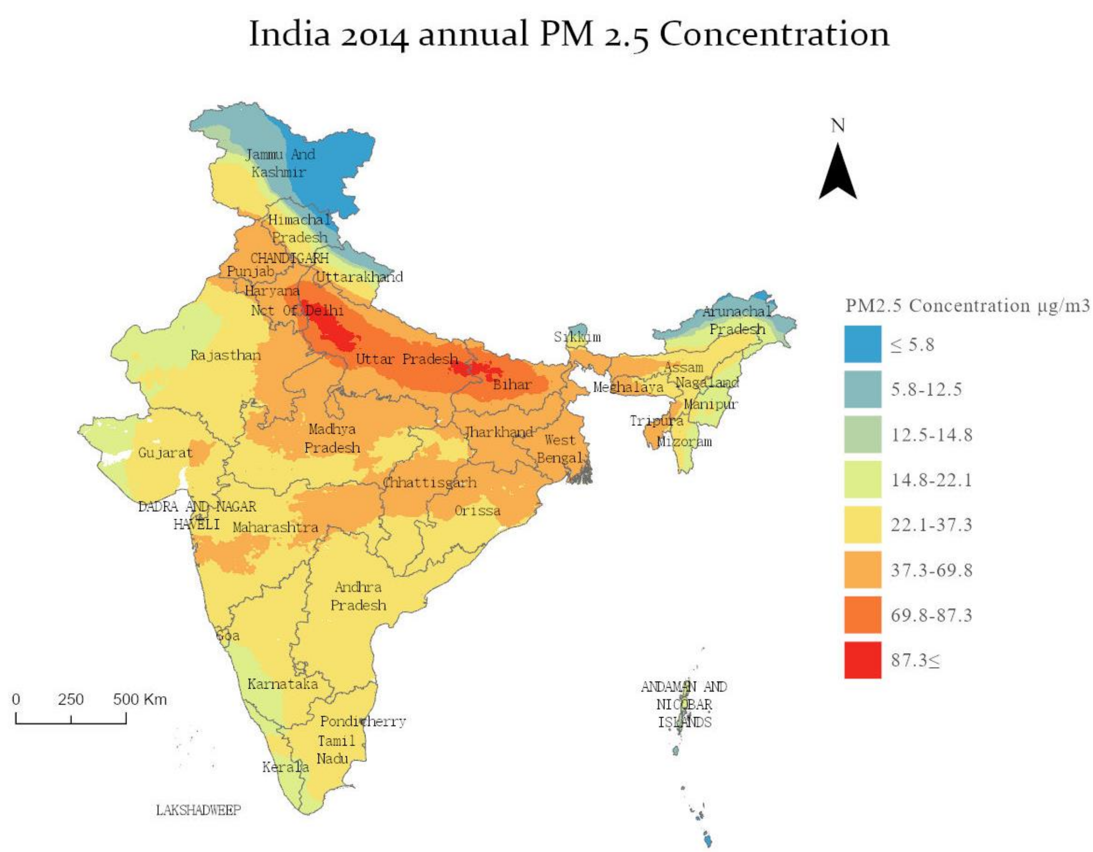


**Figure 2. India Annual $PM_{2.5}$ Concentration**

## 4.2 Consumption-based emission

### 4.2.1 Comparison between Production-based and Consumption-based $PM_{2.5}$ emission

Before the analysis of consumption orientation, we should first understand the difference between consumption-based and Production-based method. This research classifies the 65 sectors of GTAP into 12 categories to summarize the small pieces of industries. Figure 3 and Figure 4 show the difference in the proportion of emissions from different categories in the two analysis methods.

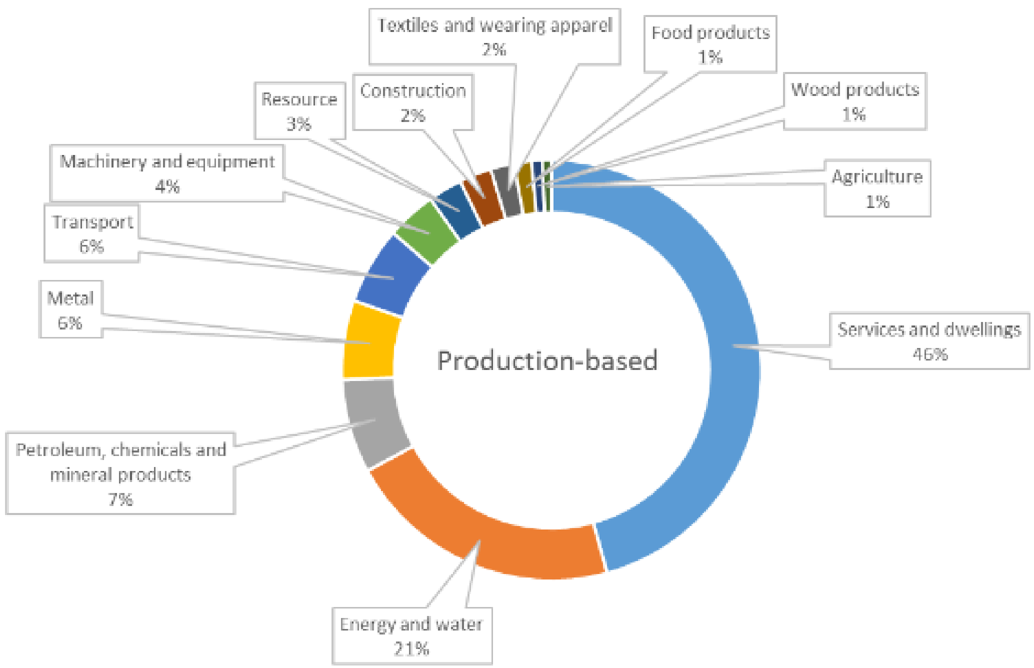


**Figure 3. PM2.5 emissions on production-based accounting**

In Figure 3, there are apparent differences in the proportion of various species. Services and dwellings accounted for the most substantial portion of total emissions, reaching 46%, followed by energy and water, accounting for 21% of the total emissions. Only these two categories accounted for 2/3 of the total emissions, while other types accounted for a tiny proportion. Based on this analysis method, we find the sources and types of $PM_{2.5}$ emissions most intuitively. Still, if we need to control the corresponding emissions, we need better emission reduction technologies to control pollution. This accounting method is not able to reflect the objective fact of pollution transfer. International trade makes raw material producing countries take more pollutions, and the consumer groups should pay these problems. Therefore, the use of consumption-based accounting plans the responsibility of pollution, to achieve joint prevention and control.

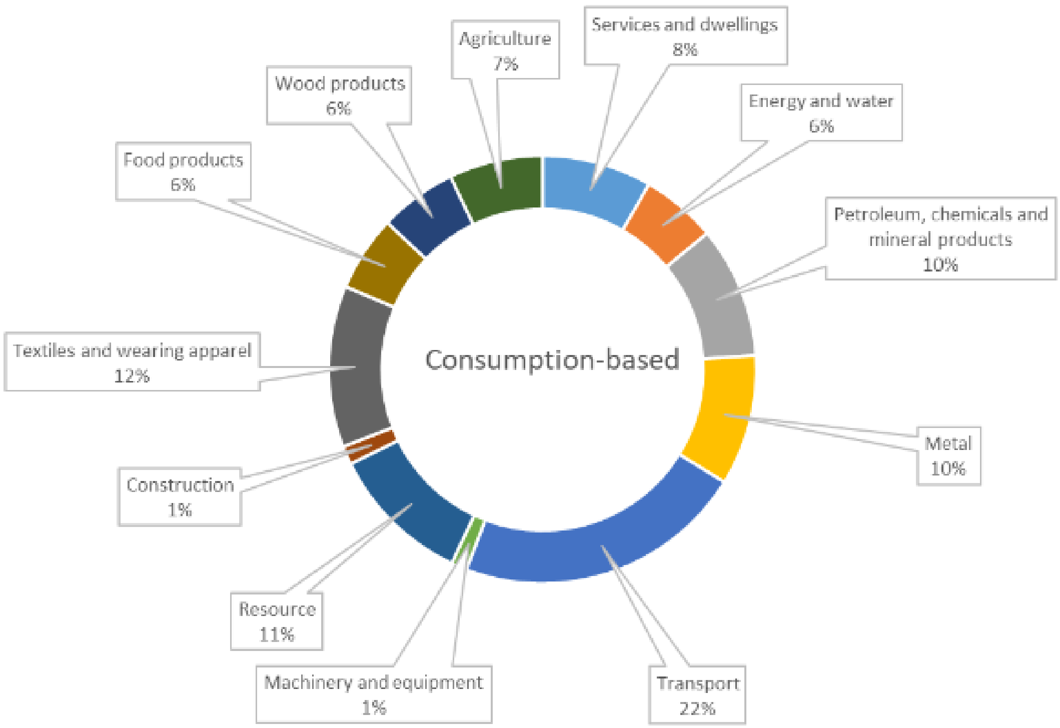


**Figure 4. PM2.5 emission on consumption-based accounting**

In Figure 4, consumption-based categories are more uniform, and the distribution types are significantly different from production-based accounting. Service & draining and energy & Water accounted for only 8% and 6% of the total, while transportation accounted for 22% of the total pollution. Besides, the proportion of various products and raw materials increased significantly. Therefore, in the process of trade, the pollution caused by raw materials as output is more prominent.

### 4.2.2 Contribution of domestic consumption VS international consumption

The input-output table by GTAP accurately gives back the total amount of domestic trade and international trade. It divides the total amount of emissions in EDGAR according to countries. In Figure 5, India's domestic consumption is 5,549 Gg, accounting for 88% of the total emissions.

The consumption of the remaining countries and regions caused emissions of 762 Gg, accounting for 12% of the total pollution. The pollution calculated here is direct and does not include the environmental impact caused by the production of raw materials. The pollution emission caused by international trade is lower than that of domestic consumers. Therefore, the effect of international trade will be analyzed separately.

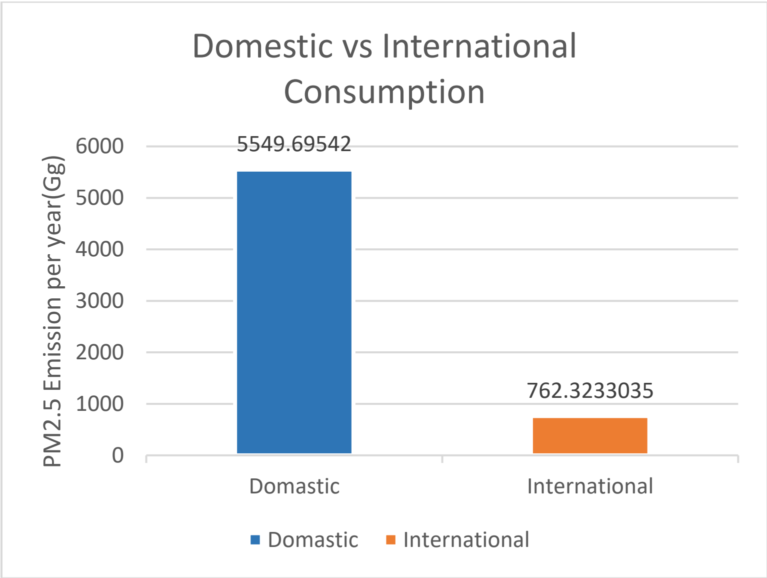


**Figure 5. Domestic consumption and international consumption**

Comparing the $PM_{2.5}$ emissions caused by consumption types in domestic and international consumption in Figure 6, the emissions of foreign consumers in service & dwellings and resources are more evident than those of domestic consumers. The demand for local consumers in agriculture, energy & water, and construction & transport is higher than that of external consumers. The proportion of emissions from food products, wood products, metal, textiles & wearing apparel, petroleum, chemicals & mineral products, and machinery & equipment is at the same level. The reason for this difference comes from the difference in main consumption targets between domestic and abroad. On the one hand, this category includes all emissions related to residential, so it contains the largest number of emission species. On the other hand, it proves that $PM_{2.5}$ emission caused by human life is higher than that of industrial consumption. Therefore, limiting the $PM_{2.5}$ emission caused by residential related activities would make significant contribution to the control of $PM_{2.5}$.

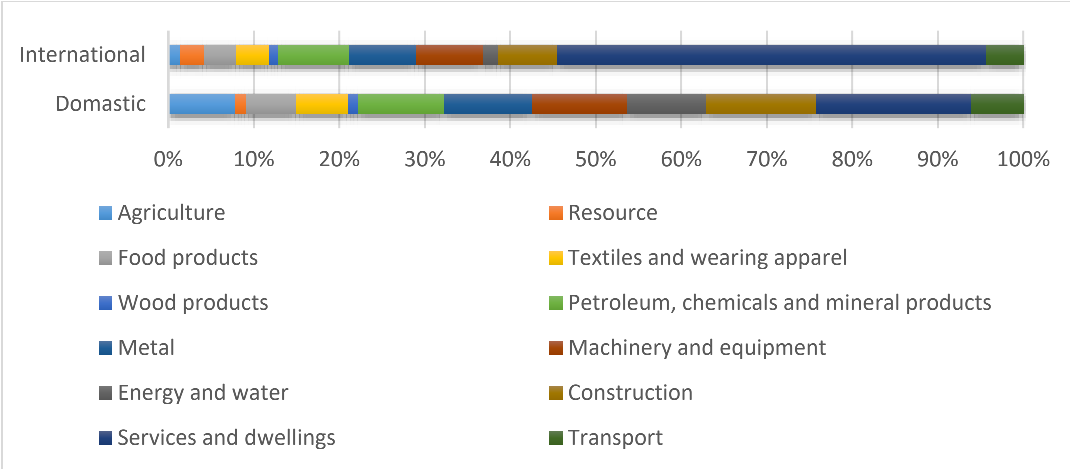


**Figure 6. Comparison the categories of domestic and international consumption**

### 4.2.3 $PM_{2.5}$ by other countries

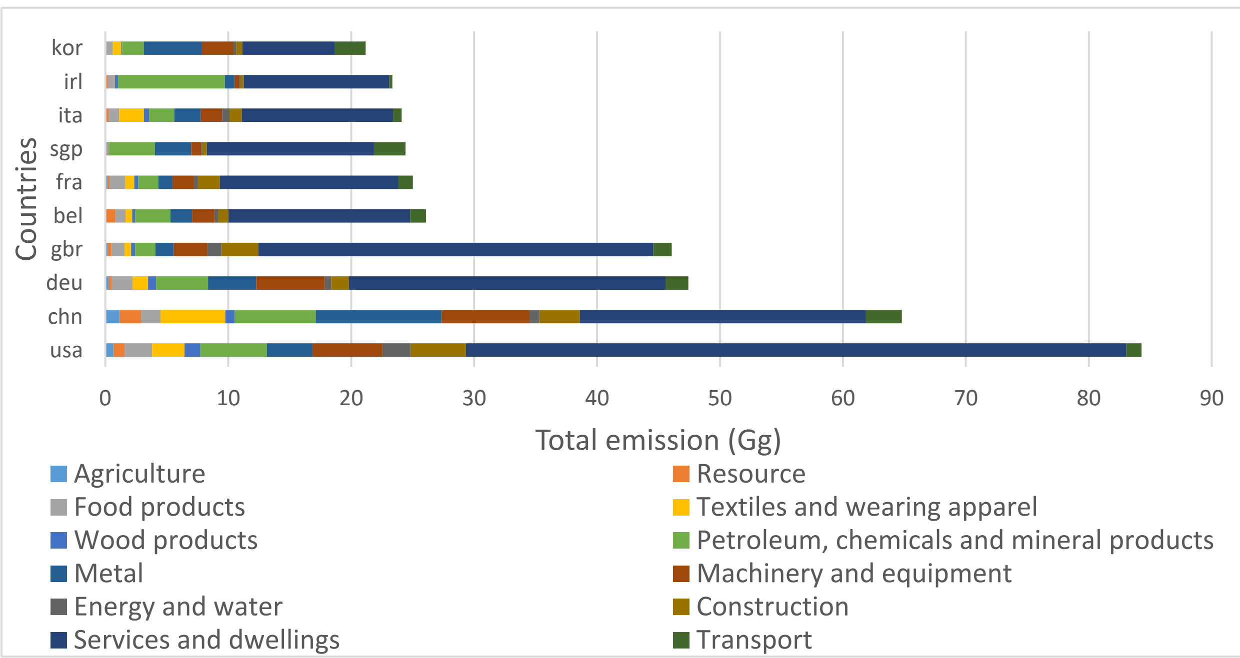


**Figure 7. Top 10 countries' consumption causing PM2.5 pollution in India**

The top 10 countries that cause $PM_{2.5}$ impact on India are the USA, China, Germany, the UK, Belgium, France, Singapore, Italy, Ireland, and South Korea, as in Figure 7. These ten countries account for 51% of the total pollution. Therefore, these countries are considered to have a major impact on premature death in India in subsequent health impact analysis. Among them, the consumption-based emissions of the USA, China, Germany, and the UK all exceeded 40 Gg in 2014, and even reach 84.29 Gg in the United States. Services and sinking of these countries account for the largest proportion, and the emission of other projects is different. Among them, Ireland's petroleum, chemical & mineral products are higher than in other countries, which points out that the trade has a significant contribution to the pollution of India.-

### 4.3 Premature mortality by $PM_{2.5}$

The baseline mortality rate used in this research is calculated regarding India's 2014 disease mortality benchmark data provided by GBD 2010, and the basic death incidence for COPD, IHD, stroke, LC are 65.13, 106.46, 50.25 and 5.61 per 100,000 people, respectively. After selecting the parameters used in the IER curve according to GBD 2013, the relationship between long-term exposure to $PM_{2.5}$ concentration and relative risk is in Figure 8. With the increase of $PM_{2.5}$ concentration, IHD increased rapidly in the low-value region and increased linearly after 20 μg / $m^3$. The LC and COPD curves increased linearly, and the slope of LC was more prominent. The relative risk of stroke increased rapidly with the increase of exposure concentration and tended to be flat after reaching 70 μg / $m^3$.

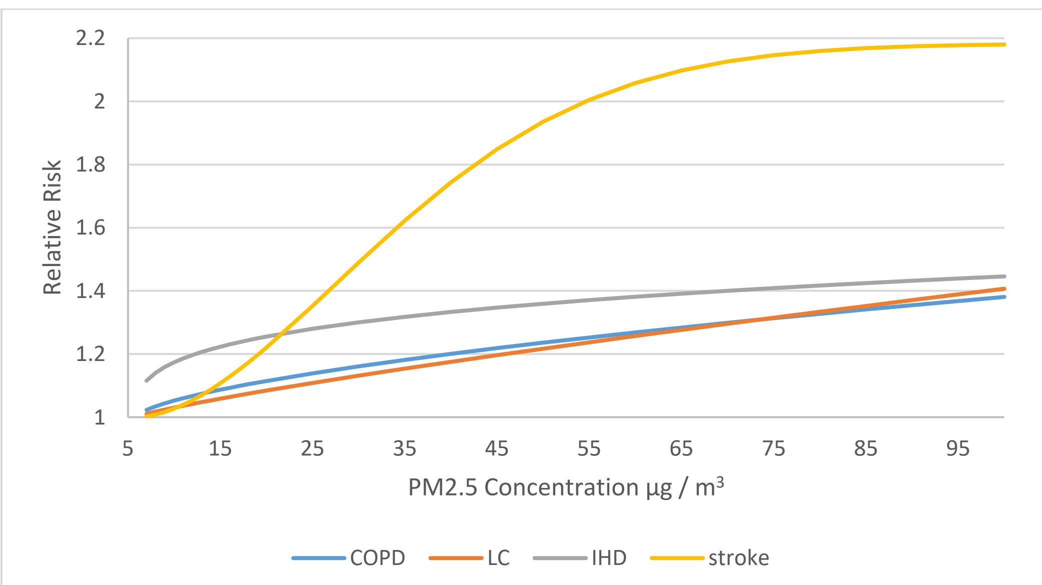


**Figure 8. Relationship between Relative Risk (RR) of chronic obstructive pulmonary disease (COPD), ischemic heart disease (IHD), stroke and lung cancer (LC) and PM2.5 concentration**

### 4.4 Health impact by international trade

Zhang et al. (2017) indicated that the derived $PM_{2.5}$ emission grid multiplied by the high-resolution global $PM_{2.5}$ concentration data could obtain the exposure level caused by long-term exposure to $PM_{2.5}$ from the perspective of consumption. Then with the IER model, the population data and pollution exposure level are combined to obtain a map of four health effects and premature deaths caused by long-term exposure to $PM_{2.5}$.

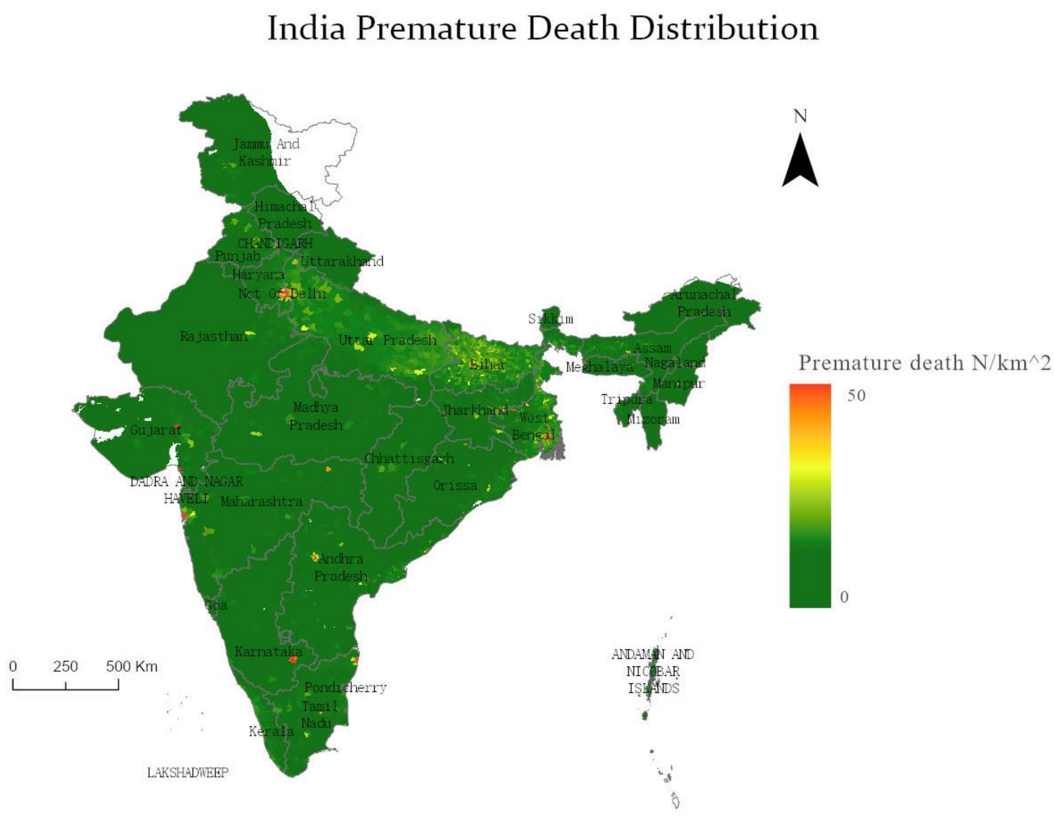


**Figure 9. High resolution (1 km × 1 km) premature death map**

In Figure 9, except for Jammu and Kashmir in the northeast, most of the areas have premature death due to long-term exposure to $PM_{2.5}$. In addition to the similarity of most regions, Haryana, Uttar Pradesh, and Bihar are three regions with high average $PM_{2.5}$ concentration, so the number of premature deaths per unit area is higher than that of other regions, a patchy light green to yellow on the map. However, the urban areas with a large population, such as NCT of Delhi, Ahmedabad, Mumbai, Bangalore, and Chennai, are small red spots on the map. On the one hand, the population density of these cities is higher, and the number of premature deaths per unit under the same conditions is more elevated. On the other hand, the same areas share the high-density population concentration and high $PM_{2.5}$ emission. Therefore, high-density population aggregation is positively related to the increase of $PM_{2.5}$ concentration because it leads to an increase of corresponding more anthropogenic activities, which leads to a rise of $PM_{2.5}$ concentration and the growth of premature death rate.

Through the calculation of IER, we get the health risks of four chronic health diseases caused by long-term exposure to $PM_{2.5}$. In 2014, the number of premature deaths caused by long-term exposure to $PM_{2.5}$ in India was about 780,000. The proportions of ischemic heart disease (IHD), stroke, chronic obstructive pulmonary disease (COPD) and lung cancer (LC) were 44.6%, 34.7%, 19.2%, and 1.5%, respectively. The premature deaths caused by domestic consumption demand and foreign consumers were 691,000 and 94,000 (Figure 10).

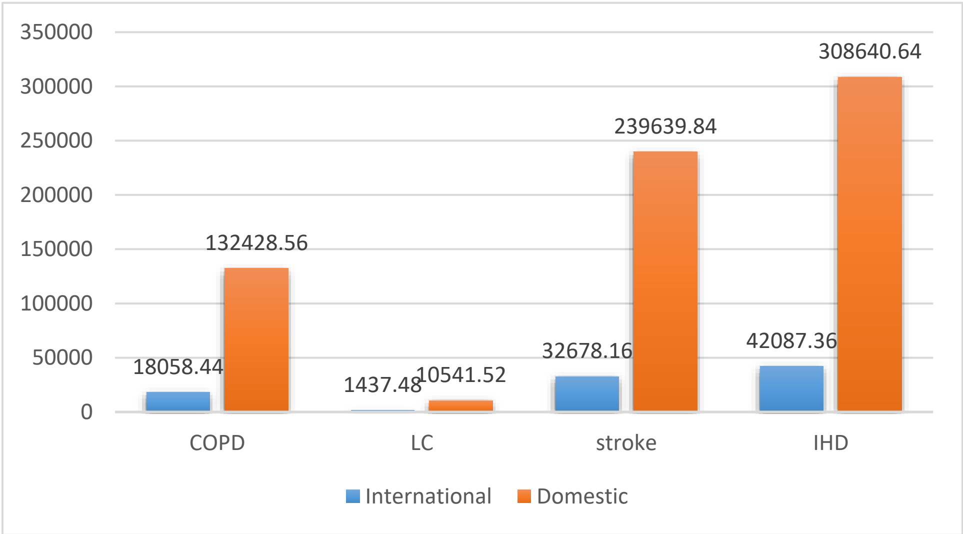


**Figure 10. Premature death by four PM2.5-related disease**

| | Agriculture | Resource | Food products | Textiles and wearing apparel | Wood products | Petroleum, chemicals and mineral products | Metal | Machinery and equipment | Energy and water | Construction | Services and dwellings | Transport |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| usa | 84.5 | 109.8 | 279.2 | 328.5 | 160.2 | 673.5 | 462.1 | 709.0 | 285.7 | 558.5 | 6684.0 | 154.3 |
| chn | 144.8 | 215.5 | 197.9 | 656.9 | 94.9 | 819.2 | 1274.7 | 889.6 | 104.6 | 406.1 | 2896.0 | 362.4 |
| deu | 36.0 | 30.3 | 209.4 | 156.1 | 81.5 | 527.1 | 486.4 | 694.9 | 65.6 | 179.5 | 3204.0 | 231.6 |
| gbr | 26.1 | 39.0 | 128.9 | 66.8 | 40.4 | 205.3 | 186.6 | 341.9 | 143.0 | 371.3 | 3998.3 | 185.4 |
| bel | 11.7 | 90.6 | 101.8 | 67.2 | 31.3 | 356.7 | 218.3 | 228.3 | 39.7 | 101.4 | 1838.7 | 159.5 |
| fra | 24.0 | 18.1 | 159.6 | 91.3 | 40.9 | 203.2 | 142.8 | 217.2 | 40.7 | 221.6 | 1808.0 | 145.4 |
| sgp | 0.3 | 0.6 | 26.6 | 4.4 | 7.5 | 463.3 | 367.2 | 99.9 | 12.5 | 44.6 | 1692.6 | 318.2 |
| ita | 9.2 | 23.0 | 108.0 | 249.1 | 52.4 | 256.1 | 268.9 | 215.9 | 74.2 | 124.5 | 1530.9 | 86.4 |
| irl | 8.4 | 18.0 | 60.1 | 6.5 | 35.1 | 1081.3 | 98.9 | 49.0 | 10.7 | 33.7 | 1472.4 | 32.3 |
| kor | 11.3 | 1.0 | 63.6 | 86.4 | 7.7 | 219.2 | 588.5 | 319.0 | 29.6 | 61.1 | 936.3 | 310.8 |
| ita | 9.2 | 23.0 | 108.0 | 249.1 | 52.4 | 256.1 | 268.9 | 215.9 | 74.2 | 124.5 | 1530.9 | 86.4 |
| jpn | 21.6 | 2.4 | 71.7 | 34.5 | 19.9 | 209.3 | 203.5 | 192.2 | 102.9 | 175.4 | 1246.7 | 221.8 |
| esp | 8.3 | 19.2 | 87.6 | 56.9 | 27.2 | 168.3 | 118.6 | 207.7 | 58.4 | 201.7 | 1394.6 | 100.6 |
| bra | 13.8 | 536.2 | 53.0 | 75.0 | 19.8 | 218.1 | 91.2 | 143.6 | 40.9 | 100.9 | 1083.8 | 46.7 |
| are | 16.7 | 129.5 | 91.6 | 15.0 | 12.5 | 198.7 | 369.5 | 211.2 | 5.2 | 705.6 | 354.6 | 84.1 |
| nld | 11.4 | 8.2 | 61.0 | 51.5 | 29.8 | 92.7 | 312.5 | 149.2 | 21.2 | 55.7 | 1094.0 | 69.8 |
| can | 24.4 | 70.3 | 41.7 | 12.6 | 18.5 | 83.1 | 60.3 | 107.8 | 46.1 | 177.3 | 937.0 | 21.6 |
| swe | 5.2 | 8.6 | 32.3 | 9.0 | 36.8 | 64.0 | 64.7 | 93.3 | 13.3 | 136.1 | 830.8 | 54.3 |
| hkg | 6.3 | 16.7 | 14.3 | 66.8 | 12.5 | 23.5 | 18.8 | 65.3 | 3.3 | 68.7 | 886.2 | 161.5 |
| che | 4.1 | 3.9 | 25.8 | 9.3 | 8.3 | 145.7 | 79.5 | 73.1 | 11.9 | 82.0 | 719.3 | 26.6 |
| mys | 16.3 | 37.3 | 38.2 | 18.4 | 9.2 | 89.7 | 93.0 | 59.4 | 24.0 | 184.7 | 436.6 | 50.7 |
| rus | 14.3 | 128.2 | 49.4 | 10.9 | 7.0 | 22.3 | 61.0 | 44.4 | 31.9 | 67.3 | 582.9 | 28.1 |
| aus | 20.8 | 62.7 | 29.7 | 9.8 | 14.7 | 41.2 | 31.6 | 29.3 | 18.2 | 87.2 | 625.1 | 53.7 |
| dnk | 5.3 | 3.7 | 24.7 | 23.8 | 11.0 | 63.8 | 54.8 | 51.4 | 14.1 | 22.6 | 673.8 | 62.9 |
| isr | 10.9 | 5.6 | 33.2 | 13.9 | 8.0 | 70.2 | 45.5 | 282.0 | 27.1 | 49.9 | 403.6 | 51.2 |
| vnm | 72.7 | 59.9 | 236.1 | 132.7 | 5.7 | 60.4 | 69.5 | 70.4 | 6.6 | 31.7 | 223.1 | 4.5 |
| tur | 16.6 | 6.3 | 61.0 | 163.4 | 11.4 | 104.2 | 49.3 | 108.4 | 7.3 | 49.4 | 341.1 | 43.9 |
| aut | 0.8 | 6.0 | 37.1 | 10.9 | 12.0 | 70.3 | 52.8 | 61.3 | 5.3 | 21.3 | 591.1 | 59.5 |
| idn | 16.1 | 4.6 | 42.6 | 62.2 | 15.0 | 90.6 | 91.9 | 59.9 | 8.7 | 234.1 | 272.2 | 28.2 |
| fin | 2.1 | 3.7 | 17.2 | 5.1 | 20.1 | 24.9 | 76.4 | 47.8 | 18.6 | 27.5 | 636.7 | 22.2 |
| sau | 12.7 | 108.0 | 168.9 | 6.2 | 3.7 | 46.7 | 71.5 | 34.7 | 36.1 | 228.3 | 70.2 | 16.6 |

**Figure 11. Premature death number from 30 countries**

Figure 11 shows the number of premature deaths caused by the trade in India by the 30 countries with the greatest pollution impact under consumption-based accounting. Excluding several countries, the number of deaths caused by services & dwellings in other countries is more than 500, considered as the leading cause of premature death of Indian in international trade. Secondly, the number of premature deaths caused by petroleum chemicals and mineral products & metal, machinery & equipment, and construction was the second major factor. The premature death caused by other categories in international trade is a secondary factor. In all units, the highest number of premature deaths was caused by services & dwellings in the United States, which reach 6,684 death per 100,000 people.

The three countries that contribute the most to the premature death of India's international trade are the United States, China, and Germany. The total number of premature deaths in these three countries are 10,489, 8,062, and 5,902. It accounts for 25% of the total premature deaths in 141 countries and regions. Ten countries of top consumptions contribute 50% of the total deaths. As a result, the United States, China, and Germany are mainly responsible for the health impact of $PM_{2.5}$ produced by consumption on the Indian population. Britain, Belgium, France, Singapore, Italy, Ireland, and South Korea have secondary responsibility for health effects.

# 5. Discussion

## 5.1 Comparison to previous research

This study used MRIO combined with IER to investigate premature deaths in India in 2014 due to long-term exposure to $PM_{2.5}$. The result shows that the number of premature deaths in India is about 770,000 in 2014. Compared with Lim et al., (2012), the premature deaths in India in 2010 is estimated to be 600,000. From 2010 to 2014, India's $PM_{2.5}$ emissions increased by 19%, the total population increased by 5%, and the number of premature deaths should increase by 25% to approximately 750,000. Therefore, the conclusions of this study are consistent with Lim's research. In terms of the proportions of the four diseases, the proportions of IHD, stroke, COPD, and LC were 44.6%, 34.7%, 19.2%, and 1.5%, respectively. However, Chowdhury et al. (2016) used the NLP risk function to estimate 54.5% of premature deaths attributable to chronic obstructive pulmonary disease (COPD), 24.0% attributable to ischemic heart disease (IHD), stroke accounted for 18.5%, and 3.0% attributable to lung cancer (LC). This is different from the conclusion obtained in this research. After careful comparison, IER and NLP have differences in calculating the relationship between RR and PM2.5. This is the main reason for the low proportion of COPD in my research. At the same time, the basic mortality rate is adjusted for different age groups in Chowdhury's paper, and the original basic mortality rate is different between two research. His estimation of 440,000 premature deaths is different from the conclusion reached by Lim et al (2014). Besides, the role of PM 2.5 in the development of COPD in the environment is generally considered uncertain (Schikowski et al., 2013).

## 5.2 Limitation and future research

First, compared with the previous EE-MRIO studies, this study used the latest data. The new EDGAR emission data reclassified the pollution types. Due to the lack of studies on the original classification, this research use in the correspondence between EDGAR and GTAP, regarding previous research methods, and reclassification of newly added or reduced items according to categories. This may lead to an inaccurate result -- part of the pollution emissions are misclassified into other sectors. Secondly, the analysis in this paper combines high-resolution pollutants and population maps, and the spatial distribution of premature deaths can be clearly known through grid calculations. This is a reference for analyzing the causes of premature death and making specific management.

Future research directions should focus on the accuracy and rapid update of input and output data. It should introduce a method that combines the emission inventory with the input-output table sector. The relevant research data should be updated in time. The same type of research can generally only analyze the previous data from three or more years, which is caused by the lag in the update of the data set. If more updated and accurate data can obtain for research, there would be a profound impact on improving air quality and reducing health risks.

## 5.3 Responsibility for consumers

Since globalization, countries in the world have redistributed their industrial structures according to the relationship between supply and demand, making the world a complete industrial chain. In this process, developed countries have transferred heavy-polluting enterprises outwards, thus achieving regional purity. These highly polluting industries are transferred to developing countries such as China and India. Before globalization, each country had to deal with the pollution problems of heavy industries on its own. After the industrial transfer, many countries enjoyed the products brought by the high-polluting sectors but did not take responsibility for corresponding health risks. Thus, environmental costs are mostly hidden. This situation is frequent but severe to be discovered. Through multi-regional input-output analysis, it is possible to find out which demand causes pollution and thereby confirm the environmental responsibility that consumers should undertake.

Sustainable development requires the joint efforts of all countries. After all, the air and ocean are circulating, and the accumulation of environmental burdens in one place will eventually affect the world. Therefore, the pollution problems arising from international trade should be shared by everyone to reduce global environmental pollution.

## 6. Conclusions

This study first used the MRIO method to analyze the impact of trade on India’s $PM_{2.5}$ emissions. From 1970 to 2014, India’s $PM_{2.5}$ emissions increased year by year, mainly due to the increase in trade-generated $PM_{2.5}$ from 169 Gg to 2,997 Gg, and the proportion of total $PM_{2.5}$ emissions from 7% to 49%. Pollution emissions from trade are divided into domestic and international trade. International trade accounts for 12% of it. The pollution caused by international trade is mainly attributed to services & dwellings, and this category accounts for nearly 50% of total emissions. From a national perspective, pollution is mainly attributed to ten countries, which share 50% of total international consumption-based emissions. The next study used the IER model to analyze four health risk factors related to long-term $PM_{2.5}$ exposure, chronic obstructive pulmonary disease (COPD), ischemic heart disease (IHD), stroke, and lung cancer (LC). The results showed that the premature deaths of the population in the three regions of Haryana, Uttar Pradesh and Bihar were more serious, and the premature deaths caused by $PM_{2.5}$ in densely populated cities of NCT of Delhi, Ahmedabad, Mumbai, Bangalore, and Chennai were significant. In 2014, India's $PM_{2.5}$ exposure caused approximately 780,000 premature deaths. Among them, IHD, stroke, COPD and LC accounted for 44.6%, 34.7%, 19.2% and 1.5% respectively. The premature deaths caused by domestic and international trade were 691,000 and 94,000. The United States, China, and Germany caused 10,489, 8,062, and 5,902 premature deaths, respectively, accounting for 25% of the premature deaths caused by international trade. This study puts forward that consumer groups in international trade should take responsibility for the pollution and health issues of the country where the product is produced to achieve the goal of sustainable production and consumption.

## Citation

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## Appendix

**Table S1.** GTAP 10 sector to categories.

| No. | Sector | Sector name | Category |
|---|---|---|---|
| **1** | pdr | Paddy rice | Agriculture |
| **2** | wht | Wheat | |
| **3** | gro | Cereal grains nec | |
| **4** | v_f | Vegetables, fruit, nuts | |
| **5** | osd | Oil seeds | |
| **6** | c_b | Sugar cane, sugar beet | |
| **7** | pfb | Plant-based fibers | |
| **8** | ocr | Crops nec | |
| **9** | ctl | Bovine cattle, sheep and goats, horses | |
| **10** | oap | Animal products nec | |
| **11** | rmk | Raw milk | |
| **12** | wol | Wool, silk-worm cocoons | |
| **13** | frs | Forestry | |
| **14** | fsh | Fishing | |
| **15** | coa | Coal | Resource |
| **16** | oil | Oil | |
| **17** | gas | Gas | |
| **18** | oxt | Minerals nec | |
| **19** | cmt | Bovine meat products | |
| **20** | omt | Meat products nec | Food products |
| **21** | vol | Vegetable oils and fats | |
| **22** | mil | Dairy products | |
| **23** | pcr | Processed rice | |
| **24** | sgr | Sugar | |
| **25** | ofd | Food products nec | |
| **26** | b_t | Beverages and tobacco products | |
| **27** | tex | Textiles | Textiles and wearing apparel |

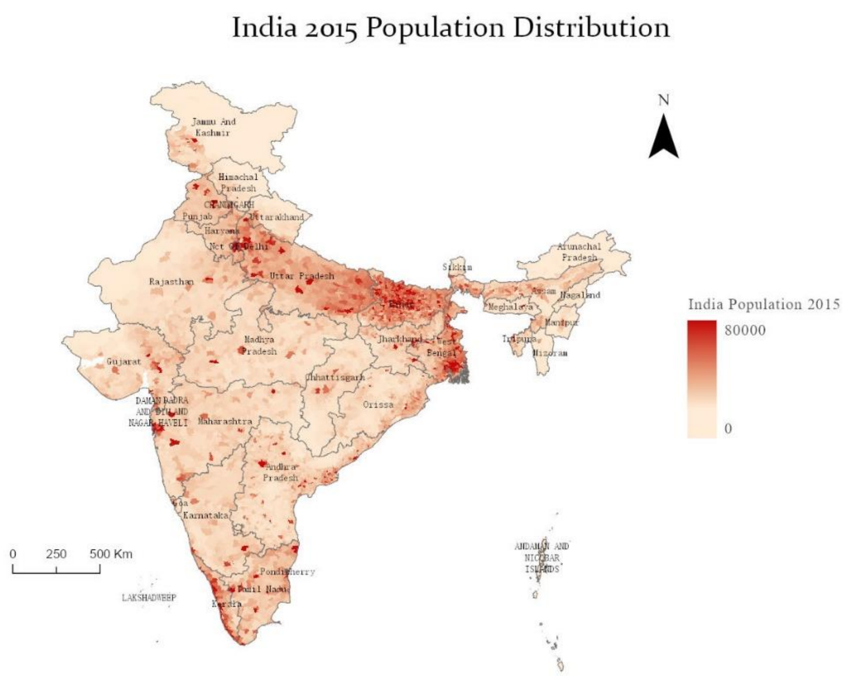
| | | | |
|---|---|---|---|
| **28** | wap | Wearing apparel | |
| **29** | lea | Leather products | |
| **30** | lum | Wood products | Wood products |
| **31** | ppp | Paper products, publishing | |
| **32** | p_c | Petroleum, coal products | Petroleum, chemicals and mineral products |
| **33** | chm | Manufacture of chemicals and chemical products | |
| **34** | bph | Manufacture of pharmaceuticals, medicinal chemical, botanical products | |
| **35** | rpp | Chemical, rubber, plastic products | |
| **36** | nmm | Mineral products nec | |
| **37** | i_s | Ferrous metals | Metal |
| **38** | nfm | Metals nec | |
| **39** | fmp | Metal products | |
| **40** | ele | Electronic equipment | |
| **41** | eeq | Manufacture of electrical equipment | Machinery and equipment |
| **42** | ome | Machinery and equipment nec | |
| **43** | mvh | Motor vehicles and parts | |
| **44** | otn | Transport equipment nec | |
| **45** | omf | Manufactures nec | |
| **46** | ely | Electricity | Energy and water |
| **47** | gdt | Gas manufacture, distribution | |
| **48** | wtr | Water | |
| **49** | cns | Construction | Construction |
| **50** | trd | Trade | Services and dwellings |
| **51** | afs | Accommodation, Food and service activities | |
| **52** | otp | Transport nec | Transport |
| **53** | wtp | Water transport | |
| **54** | atp | Air transport | |
| **55** | whs | Warehousing and support activities | Services and dwellings |

| | | |
|---|---|---|
| **56** | cmn | Communication |
| **57** | ofi | Financial services nec |
| **58** | ins | Insurance |
| **59** | rsa | Real estate activities |
| **60** | obs | Business services nec |
| **61** | ros | Recreational and other services |
| **62** | osg | Public Administration, Defense, Education, Health |
| **63** | edu | Education |
| **64** | hht | Human health and social work |
| **65** | dwe | Dwellings |

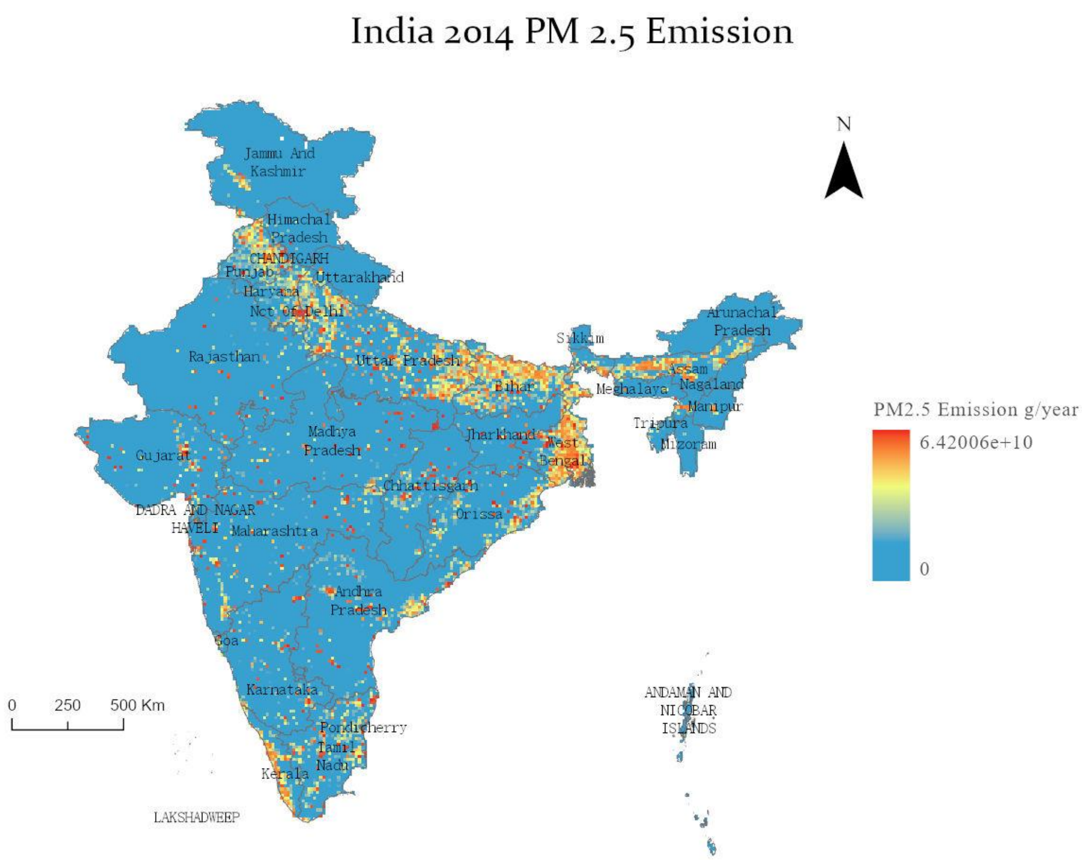
Table S2. EDGAR v5.0 classification to GTAP sectors.

| IPCC | IPCC_description | GTAP sector |
|---|---|---|
| **1.A.1.a** | Main Activity Electricity and Heat Production | 46-48 |
| **1.A.1.bc** | Petroleum Refining - Manufacture of Solid Fuels and Other Energy Industries | 32 |
| **1.A.2** | Manufacturing Industries and Construction | 15-31, 33-45, 49 |
| **1.A.3.a** | Civil Aviation | 57 |
| **1.A.3.b_no** | Road Transportation no resuspension | 48 |
| **1.A.3.b_RES** | Road Transportation resuspension | 48 |
| **1.A.3.c** | Railways | 48 |
| **1.A.3.d** | Water-borne Navigation | 49 |
| **1.A.3.e** | Other Transportation | 52 |
| **1.A.4** | Other Sectors | 50,51,55-65 |
| **1.A.5** | Non-Specified | 51 |
| **1.B.1** | Solid Fuels | 15 |
| **1.B.2** | Oil and Natural Gas | 16,17 |
| **2.A.1** | Cement production | 36 |
| **2.A.2** | Lime production | 36 |
| **2.A.3** | Glass Production | 36 |
| **2.A.4** | Other Process Uses of Carbonates | 36 |
| **2.B** | Chemical Industry | 33-35 |
| **2.C** | Metal Industry | 37-39 |
| **2.D** | Non-Energy Products from Fuels and Solvent Use | 31 |
| **2.H** | Other | 38-41 |

| | | |
|---|---|---|
| **3.A.2** | Manure Management | 1-10 |
| **3.C.1** | Emissions from biomass burning | 1-10 |
| **3.C.2** | Liming | 36 |
| **3.C.3** | Urea application | 1-10 |
| **3.C.4** | Direct N2O Emissions from managed soils | 1-14 |
| **3.C.7** | Rice cultivations | 1-3 |
| **4.A** | Solid Waste Disposal | 65 |
| **5.B** | Other | 50 |




**Appendix Figure A. High resolution population distribution map (n / km$^2$)**




**Appendix Figure A. High resolution $PM_{2.5}$ emission map (g / 100 km$^2$)**