3- Modern Air Pollution and Health Inequalities: A Global Panel Study (2000–2019 CE)

تلوّث الهواء وعدم المساواة الصحية: دراسة بانل عالمية (2000_2019م)

Done by: Waed Safar
PhD in economics, Universite d’Angers, GRANEM,
13 Allee Francois Mitterrand - 49036 - ANGERS CEDEX 01, France.
بقلم : وعد سفر
دكتوراه في الاقتصاد. جامعة أنجيه مختبر Granem
safar.waed@gmail.com

Abstract

This paper investigates the link between modern air pollution and health inequalities on a global scale, for the period 2000-2019. Using a panel model, the results show that SO2 and NOx emissions increase global burden disease inequality and cardiovascular burden disease inequality, but do not affect mental burden disease inequality. Furthermore, income inequality increases health inequality, regardless of the health outcome. Therefore, to reduce health inequalities, it is suggested to reduce pollution and ensure equitable access to the healthcare system. According to these results, a reduction in emissions can induce a win-win situation: a reduction in pollution and an improvement in health levels.

Keywords: Health inequality; Modern air pollution; Income inequality; Growth

الملخص:

تبحث هذه الدّراسة العلاقة بين تلوّث الهواء الحديث وعدم المساواة الصحيّة على المستوى العالمي خلال مدة 2000–2019. ويتم استخدام نموذج بيانات بانل (panel). وتُظهر النّتائج أنّ انبعاثات ثاني أكسيد الكبريت(SO2) وأكاسيد النيتروجين (NOx) تزيد من عدم المساواة في عبء الأمراض النّفسيّة.

علاوة على ذلك، تُبيّن النّتائج أنّ عدم المساواة في الدّخل يزيد من عدم المساواة الصحية، بغض النّظر عن نوع المؤشر الصّحي المستخدم.

وبالتالي، من أجل الحد من عدم المساواة الصّحيّة، يُقتَرَح تقليل مستويات التلوّث وضمان وصول عادل إلى نظام الرّعاية الصّحيّة. وتُشير النتائج إلى أنّ خفض الانبعاثات يُمكن أن يُحقّق وضعا رابحاً للجميع، يتمثّل في تقليل التلوّث، وتحسين مستويات الصّحة.

الكلمات المفتاحية: عدم المساواة الصّحية. تلوّث الهواء الحديث. عدم المساواة في الدّخل. النّمو.

Introduction

In the face of ongoing environmental challenges and their effects on population health, understanding the pollution–health nexus from an inequality perspective has become essential, especially within the current trajectory of economic development. Beyond its environmental consequences, ambient air pollution constitutes one of the leading risk factors for premature mortality worldwide. According to the World Health Organization WHO (2018), ambient air pollution ranks among the leading global risk factors for mortality, alongside smoking, unhealthy diets, and physical inactivity. Exposure to modern air pollution increases the risk of a wide range of non-communicable diseases (NCDs), including cardiovascular diseases, chronic obstructive pulmonary disease, cancers, diabetes, stroke, and mental health disorders. As such, pollution is no longer merely an environmental issue, it is fundamentally a development and equity concern.

Over the last two decades, a striking paradox has emerged. While many countries—particularly high-income economies—have successfully reduced "classic" pollutants through stricter environmental standards, improved monitoring systems, and cleaner technologies, the overall global health burden attributable to pollution has not declined proportionally. Pollution-related mortality remains alarmingly high, estimated at around 9 million deaths annually worldwide (Landrigan, 2017). This apparent stability conceals an important structural transformation in pollution nature. Although mortality associated with traditional forms of pollution has declined in some regions, deaths attributable to modern ambient air pollution have increased markedly over time. Global mortality linked specifically to ambient air pollution rose from approximately 2.9 million deaths in 2000 to 4.2 million in 2015, reaching about 4.5 million deaths in 2019 (GBD, 2019). These figures highlight the growing impact of industrial emissions, fossil-fuel combustion, transport expansion, and rapid urbanization, which have amplified the importance of modern pollutants such as sulphur oxides (**SO_2**) and nitrogen oxides (NOx).

Importantly, the burden of pollution is not evenly distributed across countries. The majority of pollution-related deaths (92%) occur in low- and middle-income countries, where regulatory enforcement, environmental governance, and health-system capacity are often more limited. Yet beyond differences in average mortality and morbidity levels, descriptive evidence suggests that health inequality itself differs markedly across income groups. Figures 1 and 2 reveal that health inequality persists across all country groups, regardless of the health dimension considered. However, disparities are substantially more pronounced in low- and middle-income countries (LMICs). In 2019, inequality in the global burden of disease reached approximately 0.25 in LMICs, compared with around

0.10 in upper-middle-income countries (UMICs) and 0.09 in high-income countries (HICs). A similar pattern is observed in 2000, indicating that these disparities are persistent rather than transitory. These figures confirm the existence of structurally higher health inequalities within LMICs and suggest that the distributional dimension of health outcomes differs substantially across levels of economic development.

This evidence raises a fundamental question: does modern air pollution contribute not only to deteriorating health on average, but also to widening health inequalities across countries? While the pollution–health relationship has been extensively studied, most of the empirical research focuses on average health outcomes such as mortality, life expectancy, or hospitalization rates. A smaller strand of literature examines heterogeneous effects across socioeconomic groups, yet often without directly measuring health inequality through formal inequality indices. Moreover, the few studies that explicitly regress health inequality measures on pollution indicators are largely confined to single-country contexts—particularly China—limiting the generalizability of their conclusions. As a result, the global distributional consequences of modern air pollution remain insufficiently explored.

This paper aims to fill this gap by investigating the impact of modern air pollution on health inequalities at a global scale over the period 2000–2019. We focus on three World Bank income groups—high-income countries (HICs), upper-middle-income countries (UMICs), and low-middle-income countries (LMICs)—and employ a balanced panel dataset that combines cross-sectional and time-series dimensions. To our knowledge our study is the first research that investigate the effect of modern air pollution on burden disease inequality, from a global perspective. This study takes a global scale, in order to develop solutions that transcend borders, and to take global action on all major moderate pollutants, for an equitable realization of global health. Moreover, in this study we measure health inequality using Gini indicator, to respond to limits of existing studies. Finally, our model is a Panel data, that combines time series and cross-sectional data, which enables us to reach the econometric model specifications and obtain more accurate conclusions. Our contribution is threefold. First, we provide global evidence on the distributional effects of modern air pollution, moving beyond country-specific analyses. Second, we adopt a morbidity-based inequality framework that allows a more nuanced assessment of health disparities. Third, we examine whether economic development moderates the relationship between pollution and health inequality by introducing an interaction term between GDP and pollution, thereby shedding light on whether growth mitigates or amplifies environmental health disparities.

The remainder of the paper is organized as follows. Section 2 reviews the related literature. Section 3 presents the econometric framework, variables, and data sources. Section 4 discusses the empirical results and their implications. Section 5 concludes with policy recommendations and directions for future research.

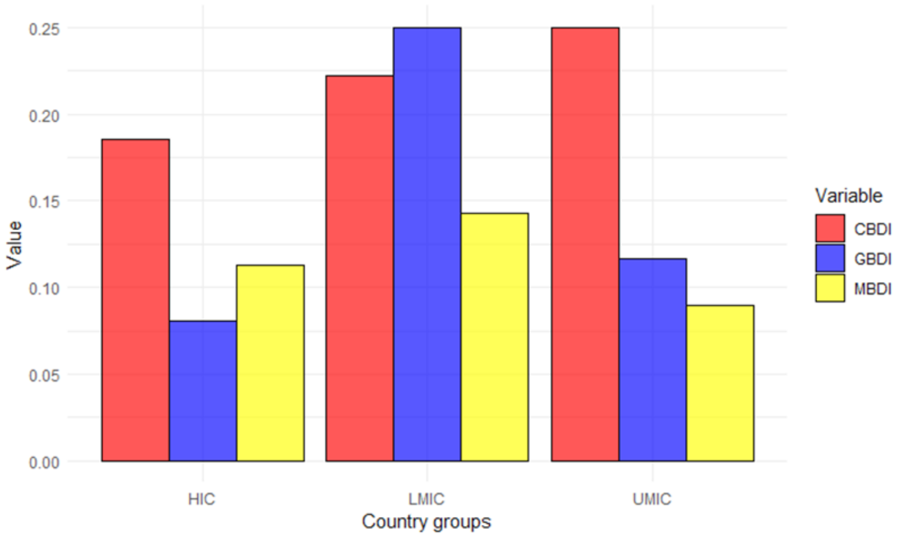

Figure 1. Health inequality by country groups for the year 2000. Source: Author's calculations.

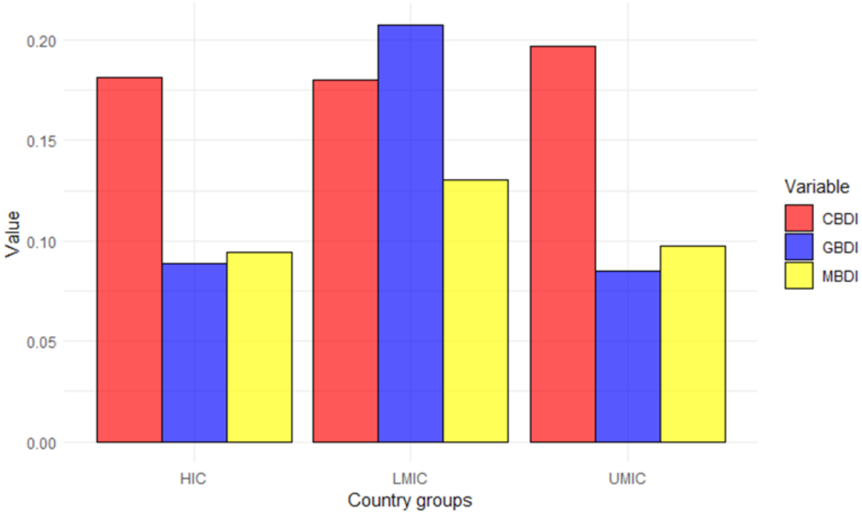

Figure 2. Health inequality by country groups for the year 2019. Source: Author's calculations.

Section 2: Literature review

The ongoing problem of air pollution and its increasingly serious health consequences have prompted several empirical studies to investigate the relationship between air pollution and health, as well as health inequalities at micro- and macro-economic levels, see Table 1.

Within this research, primary studies have focused on the simple effect of air pollution on health. To estimate this relationship, they have used alternative air pollution indicators such as NOx, CO2, and SO2 emissions, as well as PM exposure.

At the macro level, studies have used air pollution indicators to study their impact on numerous health outcomes, such as mortality rate, infant mortality rate, hospitalization rate, DALYS, and life expectancy (Richardson et al., 2013; Lavaine, 2015; Chen and Chen, 2020; Lelieveld et al., 22020; Wang et al., 2022). These studies have shown that there is almost a clear consensus that air pollution contributes to greater, and more hazardous health risks. For example, Lavaine (2015), using Ordinary Least square (OLS) and Fixed-Effect (FE) models finds that NO2 emissions increase mortality rates in French departments over the period 2000-2014. Similarly, Wang et al. (2022) find that industrial NOx and SO2 emissions increased infant mortality rates in China. Chen and Chen (2020) find that NO2, SO2, O3, and CO emissions, as well as exposure to PM2.5, increase the mortality rate from chronic obstructive pulmonary disease (COPD) in China for the period 2015-2018. Lelieveld et al. (2020) conclude that eliminating fossil fuel emissions., all controllable emissions caused by human activities increases the average life expectancy of individuals from 1.1 years to 1.7 years worldwide.

As at the macro level, at the micro level, it has been well documented that environmental pollution plays a risky role in various health outcomes of individuals, such as physical discomfort, self-reported health status, and cognitive abilities (Johnson and Parker, 2009; Cacciottolo et al., 2017; Zhang et al., 2017; Dzhambov et al., 2018). For instance, Cacciottolo et al. (2017) find that exposure to PM2.5 increased the risk of Alzheimer's among elderly women in the USA. In addition to the effect of pollution on mental health, Johnson and Parker (2009) find that exposure to air pollution increased the risk of self-reported cardiovascular disease in USA among people aged 30 and over during the period 1999-2005. A 10 mg/m3 increase in PM2.5 exposure was associated with a slight increase in the risk of hypertension (adjusted odds ratio (OR) 1.05, 95% confidence interval (CI) 1.00-1.10) and heart disease (1.0895% CI 1.00-1.16). Alongside studies that have investigated the effect of pollution on health, many studies have investigated the effect of pollution on health inequality in different environmental and socioeconomic contexts (Neidell, 2004; Drabo, 2013; Richardson et al., 2013; Cacciottolo et al., 2017; Chen and Chen, 2020). Indeed, these studies test whether some groups of populations, regions, or countries are more vulnerable than others to the health effects of pollution. To this end, they study and compare the heterogeneous effect of pollution on the health status of different socioeconomic groups. For example, Richardson et al. (2013) find that environmental injustice contributes to mortality disparities between Western and Eastern Europe, where mortality rates due to circulatory disease are more pronounced in low-income regions (Eastern Europe). In addition, Cacciottolo et al. (2017) find that people with low levels of education and migrants are more vulnerable to PM10 in Italy over the period 1990-2010. Neidell (2004), meanwhile, finds that the effect of carbon monoxide pollution increases asthma hospitalizations among children of lower socioeconomic status, indicating that pollution is one of the potential mechanisms by which socioeconomic status influences health. According to Chen and Chen (2020), the effect of pollution is greater on the health of lower socioeconomic groups. They explain that despite wealthier and better-educated groups are more sensitive to pollution, but they are more likely to adopt avoidance behaviour to mitigate the negative effect of pollution, such as improved access to medical care, and individual demand for medical insurance.

Recently, a new stream of literature has analysed the effect of air pollution on health inequalities in a different way of later studies, see Table III.2. These studies examine the direct effect of pollution on health inequality in the same regression (Azimi et al., 2019; Yang and Liu, 2018; Liao et al., 2023). To assess health inequality, they use alternative indicators such as Gini index, Theil index, concentration index (CI), and slope inequality index (SII). Yang and Liu (2018), using a hierarchical linear model (HLM), investigate the effect of CO2, SO2, and NOx emissions on health inequality, measured through Gini index. Their results show that pollution increases the level of health inequalities. In addition, using the Generalised method moment model (GMM), Azimi et al. (2019) find that unequal exposure to NOx and SO2, measured by the Theil index, leads to inequality in tuberculosis mortality. More recently, using the recentred influence function (RIF) regression method, Liao et al., 2023 measures the effect of individual pollution exposure on three alternative socioeconomic health inequality indicators, i.e., the concentration index, the Wagstaff index (WI), and the Erreygers index (EI). Their results show that, irrespective of the socioeconomic inequality health indicator, environmental pollution increases socioeconomic health inequality, i.e., exposure to pollution increases the concentration of poor self-reported health, chronic disease, and physical discomfort among the poorest people.

In summary, few studies have examined the impact of pollution on health inequality in the same regression directly, i.e., measuring health inequality through specific indicators, so the underlying mechanism still deserves to be explored. Furthermore, in the three existing studies cited above, the relationship between pollution and health inequality was only investigated at the China case study level, so there is no broader conclusion. To this end, this study aims to further explore the mechanisms explaining the link between pollution and health inequality from a global perspective to draw conclusions on a global scale that help in the establishment of policies beneficial to the overall community.

Table 1. Summary of empirical studies analyzing the impact of pollution on health and health inequality.

Authors	Country	Year	Methodology	Pollution indicator	Health indicator	Results
Richardson et al. ((2013	NUTS2 regions	–2004 2008	OLS	PM10	Mortality rate	Pollution exposure heterogeneity • contributes to disparities in mortality rates between eastern and western Europe, with a higher effect on eastern Europe Low–income • regions are the most vulnerable to pollution in terms of mortality rates caused by circulatory diseases in eastern Europe and respiratory disease among .men in western Europe
Lavaine ((2015	France	–2000 2004	OLS; FE; D–KS.E[1]	NO2; O3; PM10	Mortality rate ((all causes	There is a positive link • between NO2 levels and mortality rate, with higher .risk on women There is socioeconomic • health inequalities between French departments relative .to income inequalities
Lelieveld et (al. (2020	Global	2015	—	PM2.5	Loss of life expectancy	Exposure to air pollution • causes hazardous health .effects Air pollution effect exceeds • the effect of tobacco smoking .on mortality rate
Chen et al. ((2021	China	–2015 2018	Quasi–Poisson GAM[2]	PM2.5; SO2; NO2; O3; CO	COPD–related mortality	All air pollutants show a • positive link with increases COPD–related mortality among people aged of 60 .and older

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(1)– D–KS.E means Driscl and Kraay standard errors methods, respectively

(2)– GAM means general additive model.

Wang et (al. (2022	China	;2012 ;2014 2016	MOL (micro); OLS; FE (macro)[3]	Industrial SO2; NOx; Smoke	SRH; Infant mortality rate	Air pollution decreases • SRH at micro-economic level and increase infant mortality rate at the macro-economic level • The interaction term between air pollution and GDP show that economic growth decrease the harmful impacts of air pollution on public health at the macroeconomic level • The interaction term between air pollution and individual income show that the increase in personal income increase the negative effects of air pollution on public health at the micro .economic level
Cacciottolo et al. ((2017	USA	-1990 2010	BME[4]	PM2.5	Cognitive impairment	PM2.5 exposure promotes brain aging and Alzheimer's pathogenesis in older .women
Giaccherini et al. ((2021	Italy	-2013 2015	2SLS[5]	PM10	Hospitalizations (asthma, pneu- (monia, COPD	PM10 increases daily • hospitalizations per 100,000 .residents Elderly, low educated • people, and migrants most .affected
Meisner et (al. (2023	Macedonia	2010	—	PM10; PM2.5	DALYs	Exposure to fine particulates negatively affects day-to-day health and ability to .work

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(1) - This article uses multivariate ordered Logit (MOL) model for micro-economic database, and OLS and FE are used for macro-economic database. For micro-economic model health dimension is apprehended through self-reported health status, however infant mortality rate is used as health indicator in macro-economic model

(2)- This article is an epidemiological article that use Bayesian Maximum Entropy (BME) method.

(3) - 2SLS stands for two-stage least square method. This article use public transports strikes as Instrumental variable (IV) for endogenous air pollution. Health is apprehended through daily hospitalizations

Table 2. Summary of empirical studies analyzing the impact of pollution on health inequality (new stream).

Authors	Country	Year	Methodology	Pollution	Health outcome	Inequality index	Results
Azimi et (al. (2019	China (31 (regions	–2006 2015	GMM; Quantile regression	SO2; NOx	Perinatal mortality rate; Tuberculosis mortality rate	Theil	Inequality in pollution • emissions induces inequality in tuberculosis .mortality No effect on perinatal • .mortality inequality Income inequality has • no effect on .socioeconomic health inequality
Liao et al. ((2023	China	–2010 2014	RIF–OLS	Pollution exposure ((binary	Physical discomfort; Chronic disease; SRH	EI; CI; WI	Environmental • pollution increases income–related health .inequality Pollution increases • concentration of poor SRH, physical discomfort, and chronic .disease among poorest
Yang & (Liu (2018	China	2014	HLM	CO2; SO2; NOx	SRH	Gini	Health inequality • prevalent in China and more severe in rural .areas Air pollution increases • health inequality; supports environmental–health–.poverty–trap

Section 3: Model and data

Section 3.1.: Model

This study aims to identify the general pattern between air pollution and health inequality at the level of three socioeconomic country groups. Unlike most existing studies, which have limited themselves to investigating the heterogeneous impact of pollution on health outcomes at the level of different socio-economic groups. In this study we will examine the effect of air pollution on health inequality, in the same regression, by measuring health inequality through Gini indicator. Moreover, unlike the existing studies that have been limited to the national China case of study, see Table 2, our model is studied at the level of three groups of countries, namley, low-middle-income countries (LMICs), upper-middle-income countries (UMICs), and high-income countries (HICs), to contribute to a more global understanding of health problems and their distribution on a global scale.

We believe that understanding the link between pollution and health inequality at the international scale, is crucial for global public health and essential for the development of international policies to address the challenges of global warming, the environment, and health distributions.

To build our econometric model, we use a recent database covering three groups of countries : LMICs, UMICs, and HICs, for the period 2000-2019. The country groups are defined according to the World Bank (WB) classification, which groups the world's economies into four categories regarding their income level: low-income countries (LICs), LMICs, UMICs and HICs. However, in the context of our study, we exclude LIC for several reasons, which will be discussed subsequently. First, over time, world income has increased, leading several countries to shift from low-income to low-middle-income countries, making the number of countries in the low-income group limited to 31. Consequently, the majority of people living below the poverty line are now belonging to low-middle-income countries, making the group LMICs a representative group of low socio-economic categories, which is why we consider the LMICs to be the lowest income group in our model (Fantom and Serajuddin, 2016).

In addition, low-income countries often have less reliable and less complete data on various economic, health, and pollution indicators. Including them in our study could generate significant data quality problems, which could lead to unreliable results. Moreover, given the huge differences between low-income and middle- and high-income countries in terms of economic, social, environmental, and health measures, their inclusion may create heterogeneity in our model, which could make the results inconclusive.

Finally, the number of countries belonging to the LIC group with available data is very small, which considerably reduces the representativity of this group compared to other ones.

Hence, to study the effect of pollution on health inequality across our three groups of countries, we will use the panel regressions expressed in Eq.1 as follow:

$$HI_{it} = \beta_0 + \beta_1 \; P_{it} + \beta_2 \, X_{it} + \beta_3 \; (GDP_{it} \times P_{it}) + \mu_t + \; \varepsilon_{it} \qquad (Eq.1)$$

HI is the dependent variable, expressed by three alternative health inequality indicators, namely, Global Burden Disease Inequality (GBDI), Cardiovascular Burden Disease Inequality (CBDI), and Mental Burden Disease Inequality (MBDI) at the macro level, for group of countries i in year t. Health inequality indicators are calculated by the authors, see section 3.2.

P is our main explanatory variable, which reflects the weighted annual average levels of pollution of group i in year t, for more details on the calculation of this variable see. Appendix B. To assess pollution, we use two of the principal components of modern air pollution, the sulphur oxides (SO2) and nitrogen oxides (**NOx**) indicators, alternatively, collected from

Our World in Data (OWID). Epidemiological studies have shown a significant effect of SO2 and NOx on human health hazardous. These air pollution indicators can be diffused to the atmosphere through human activities, particularly the combustion of fuels. Their health consequences include respiratory symptoms, cardiovascular disease, Alzheimer's, increased hospitality rate, and more severly, mortality rate (Boningari and Smirniotis, 2016; Kamarehie et al., 2017; Zhang et al., 2017).

The term in Eq.1 represents the group's non-observable variables, that varies over time. These unobserved group's characteristics that could influence health inequalities could be weather characteristics, geographical environment, and natural resources endowment (Wang et al., 2022). is the regression coefficient of the variable, and is the error term.

 is our control variables, namely weighted average GDP per capita, average year of schooling, and income inequality (Yang and Liu, 2018; Liao et al., 2023). In addition to those socioeconomic variables, we will use government health expenditure as health resource control variable, and the interaction term between Pollution and GDP (GDP*P).

To choose the most appropriate method for each model between Fixed-Effect (FE) and Random-Effect (RE) models, we look at the results of the Hausman test.

Table 3. Descriptive statistics of the variables.

Variable	Definition	Mean	.Std. dev	Min	Max	.Obs
Health inequality indicators "Dependent variable"						
GBDI	Global burden disease inequality ((0;1	0.144	0.067	0.08	0.253	60
CBDI	Cardiovascular burden disease inequality ((0;1	0.205	0.067	0.179	0.267	60
MBDI	Mental burden disease inequality ((0;1	0.114	0.019	0.089	0.145	60
Pollution indicator "Interested variable"						
Nox	Weighted average of nitrogen oxides (kg (per capita	18.534	10.632	6.14	42.698	60
SO2	Weighted average of sulphur dioxides (kg (per capita	16.207	8.115	6.26	32.892	60
II	Income inequality ((0;1	0.797	0.051	0.717	0.855	60
Control variables						
GDP	Weighted average GDP per capita (2017 ($ PPP	20330.4	17551.18	3493	49959.85	60

Educ	Average years of schooling ((years	13.185	2.0837	9.26	16.436	60
Exp	Weighted average health expenditure (% (GDP	3.58	2.33	1.27	7.50	60

Section 3.2: Variables

Socioeconomic factors

In most cases, the association between socioeconomic factors and illness is inversely graded, i.e. the higher the socioeconomic status, the better the health, and vice versa. Indeed, higher socioeconomic groups, with higher incomes and higher levels of education, tend to have a lower risk of physical and mental health problems and a lower mortality rate (Fang et al., 2010).

Moreover, previous studies have proved that socioeconomic factors such as GDP, education, and income inequality have significant effects on health inequality (Yang and Liu, 2018; Liao et al., 2023). Therefore, we will include these factors in our model for the followed explanations.

1- **Education:** Education plays a key role in improving health and reducing health inequalities. In most countries, education influences the future professional position of the population and, by extension, their income. This strengthens people's ability to access healthcare services and cover medical costs. In addition to the effect of improved income, educated population is better informed about the negative effects of pollution on health, hence they can take protective behaviours regarding pollution risks (Khalatbari-Soltani et al., 2022).

In this study, we use the average year of schooling as the education variable.

2- **GDP and Income Inequality**: Pritchett and Summers (1993) conclude that wealthier groups, with higher incomes, tend to have better health. Furthermore, Fang et al. (2010) shows that income inequality is the most important determinant of health inequality. Low-income groups are not always able to cover their medical expenses, and this translates into a lower level of health than high-income groups. If there is a positive relationship between income inequality and health inequality, the environment-health-poverty trap hypothesis is verified (Yang and Liu, 2018). To this end, we will assess the level of development using the weighted average GDP per capita for each group of countries, as well as we calculate income inequality for each group of countries using the GDP per capita of the countries in each group.

3- **GDP*P**: The interaction term between GDP and pollution has been used to reflect the joint effects of the two variables on health inequalities. In general, both growth and pollution can affect health disparities. So, how does the interaction between economic level and air pollution affect global health disparities? While many studies have examined the effect of pollution on health inequalities, the interaction between pollution and growth on health inequalities remains to be explored. In line with Wang et al. (2022)'s study, we will include this interaction variable to assess its effect on our outcome variable. The inclusion of this moderating effect is based on the perspective that economic growth acts as a moderating element for the impact of pollution on the health indicator.

Public health expenditure

According to Fang et al. (2010), health inequalities between groups can be explained by the government's inability to distribute health resources equitably. Indeed, Gupta et al. (2003) and Wagstaff and Doorslaer (2004) mentions that disadvantaged socioeconomic groups tend to have poorer health status due to their limited access to health care services. Therefore, to reduce health inequalities, public health spending should specifically target disadvantaged groups. To this end in line with Fang et al. (2010) and Yang and Liu (2018) studies, we use the weighted average of health expenditure as health resource control variable.

Income inequality (Gini index)

In our study, we use the Gini index to calculate income inequality between countries within each country group. The Gini index is the most popular indicator of inequality, varying between 0 and 1. If G=0, there is perfect equality between countries at the level of each country group. If G=1, there is perfect inequality between countries at group level. The Gini index can be calculated using the following equation, which considers the gap between two samples i and j.

$$G = \frac{1}{2N^2\bar{X}} \sum_{i=1}^{N} \sum_{j=1}^{N} |x_i - x_j| \qquad (Eq.2)$$

N= The number of samples

= The average GDP per capita

xi, xj , are the GDP per capita of the sample i, and j

To assess Gini index, we have used the “Gini” package in RThe same method was used to measure health inequality (Wagstaff et al., 1991).

Health inequality indicator

Health inequality is a growing concern for both policy-makers and researchers. To this end, several methods have been developed to calculate health inequality. First of all, To assess health disparities, we need a health indicator itself. Fang et al. (2010) has classified health indicators into two categories: The first category comprises the classic health indicators, reflecting mortality and morbidity status. That can be a subjective measure, such as self-reported health status of physical discomfort, or objective, like infant mortality and cardiovascular disease.

The second category encompasses more recent indicators, known as Burden disease, also known as Disability-adjusted life years (DALYs). These indicators represent a standard, objective measure of health risk. This variable combines the disease burden of years of life lost due to premature death and the fraction of years lived with disease or disability. In effect, “one DALY is equivalent to one year of healthy life lost” IHME (2019).

Given that the World Health Organization has recommended the Burden disease variable Landrigan (2017), we will adopt it as a health indicator to calculate health inequality variables in our model. To this end, we have selected three alternative health outcomes from Institute For Health Metrics and Evaluation (IHME) data, namely Global burden disease (GBD), Mental burden disease (MBD) and Cardiovascular burden disease (CBD).

Secondly, there are two approaches to calculate the health inequality indicator see Fig.3. The first approach measures pure health inequality or overall health inequality, while the second approach is used to calculate socioeconomic health inequality.

The first approach uses standard inequality indicators to assess health inequality. The indicator used to calculate pure health inequality are like those used to calculate income inequality, such as the Theil index, the Atkinson index, the ratio and the Gini index. To calculate pure health inequality, we only need the health outcome. The second approach, on the other hand, requires knowledge of two components to calculate a socio-economic health indicator: the health index and a socioeconomic variable such as income. The socioeconomic health inequality indicator can be calculated using several indicators, the most used of which are the concentration index “CI” and the slope inequality index “SII”. The slope index captures the difference in average health status between the highest and lowest socio-economic groups. The CI, which varies between −1 and 1, measures the degree of health inequality. If the CI takes a negative value, it means that disease is concentrated among the poorest, if the CI takes a positive value, it means that disease is concentrated among the wealthiest classes. If the CI=0, it means that the level of health is evenly distributed between socio-economic groups.

Following the Azimi et al. (2019) and Fang et al. (2010) studies, we choose to assess pure health inequality using the Gini index, which is recommended by (Wagstaff et al.,1991).

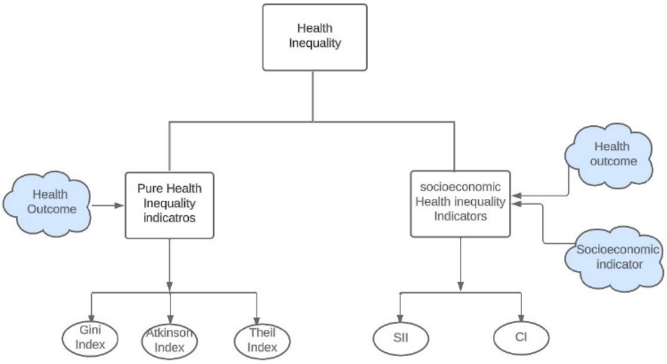

Figure 3. Diagram of health inequality measurements.

Section 3.3: Data sources

Our data takes the form of a longitudinal, strong and balanced database, which combines cross-section data (three groups of countries) and time-series data (2000- 2019). These data come from three different sources: health indicators collected from the IHME, pollution indicators from the OWID, GDP per capita, government health expenditure, and education from the World Development Indicators (WDI).

According to the summary statistics in Table III.3, we can see that average GBD inequality measured by the Gini index is 0.144, the average CBD inequality is 0.20 and the average MBD inequality is 0.114, meaning that health inequality is more pronounced with CBD over the period 2000-2019. Each time the Gini increases and tend to 1, there is an increase in health disparity. The weighted average for NOx is 18.53 kg per capita, and 16.20 kg per capita for SO2, so the level of pollution caused by NOx is higher than SO2 over the period 2000-2019. Regarding the correlation test presented in Table. 4 we can see that GBD inequality and MBD inequality are strongly correlated with NOX and SO2.

Table 4. Correlation matrix of the variables.

	GBDI	CBDI	MBDI	Nox	SO2	II	GDP	Educ	Exp
GBDI	1								
CBDI	0.054	1							
MBDI	0.922	-0.229	1						
NOx	-0.839	-0.234	-0.605	1					
SO2	-0.742	0.273	-0.654	0.825	1				
II	0.459	0.703	0.20	-0.65	-0.14	1			
GDP	-0.75	-0.497	-0.539	0.82	0.42	-0.9	1		
Educ	-0.91	-0.36	-0.779	0.81	0.52	0.90	1	1	
Exp	-0.79	-0.42	0.60	0.81	0.49	-0.88	0.99	0.9	1

Section 4: Regression results

To study the impact of air pollution on health inequalities, we use a balanced panel database. This method enables us to control for heteroscedasticity and minimize problems related to observed variables, while ensuring a politically relevant analysis (Wooldridge, 1996).

To this end, we ran two models: the Fixed-Effect model and the Random-Effect model. To select the appropriate model for our regression, we use the Hausman test. The null hypothesis (H0) of Hausman test is that both RE and FE estimates are consistent. IF p-value is lower than 0.05, than the null hypothesis well be rejected, and the alternative hypothesis (H1) is holder, meaning that RE estimates is inconsistent, hence, the FE model is selected.

In our model, the application of the Hausman panel test resulted in a P-value less than 0.05, leading us to select the FE model.

Table 5 displays the regressions results of FE model of the association between air pollution measured through SO2 emissions and alternative health inequality indicators. Model 1, 2 and 3 are defined to measure the effect of SO2 emissions on GBD inequality, CBD inequality and MBD inequality, respectively. As expected results of the first and second model show that the relationship between SO2 emission and health inequality is positive. An increase of 1% of SO2 emission per capita increases the inequality in GBD inequality of 0.44%. Also, for a 1% increase in SO2 emission per capita bring a rise of o.43% in CBD inequality. However, Model 3 reveals that there is no significant relationship between SO2 emissions per capita and inequality in mental burden disease, these results are in line with (Wang et al., 2022) and (Azimi et al., 2019) studies.

The positive relationship between SO2 emissions and health inequalities can be explained by the fact that lower socioeconomic groups pay less attention to pollution in their government programs. They are subject to less stringent environmental regulations, resulting in higher levels of air pollution and, consequently, lower levels of health than higher socioeconomic groups. These results suggest that the disparity in health levels between countries could be reduced if emission levels were specifically reduced in low socioeconomic groups.

To date, existing studies have not established a conclusive relationship between pollution and mental health. This may be explained by the complex nature of mental health problems, as well as by the fact that the effects of pollution on mental health may be indirect and influenced by other factors not considered in our model (Ventriglio et al., 2021).

Regarding the effect of income inequality on health inequality, all models represented in Table 5 show that income inequality has a negative impact on health inequality, irrespective of the health inequality indicator taken into account. These results are consistent with the studies conducted by (Fang et al., 2010), but diverge from those of (Azimi et al., 2019), who find no significant relationship between income inequality and health inequality.

Indeed, our results indicate that, in our context, higher income can exacerbate health inequality. This means that groups characterized by a higher degree of income inequality may have a higher level of health inequality.

This disparity in health affected by the unequal distribution of GDP per capita is explained by unequal access to public health resources. Groups with higher GDP per capita have better access to quality health services. These societies offer their populations health insurance, medical treatment and preventive care on an equal basis, and have a better infrastructure for healthcare delivery.

With regard to the socio-economic variable of education, we can observe that a 1% increase in the average year of schooling decreases GBD inequality by 0.326%, CBD inequality by 0.33%, and MBD inequality by 0.07%. High levels of education are often associated with better health outcomes. More educated societies are aware of the adverse effects of pollution on health and are therefore more likely to change their behaviour to adopt a healthier lifestyle, in order to prevent the negative consequences of pollution on their health.

The interaction term between SO2 and GDP decreases health inequality. These results mean that GDP attenuates the adverse effect of pollution on health inequality. Indeed, a wealthiest society accompanied by high SO2 levels, tend to have more resources to implant effective pollution control resources and health care provision, which mitigate the health impact of pollution. Thus, despite the detrimental effect of SO2 on health, its negative impact can be mitigated by an increase of GDP per capita in societies. As we see in Model 1 and Model 2 a 1 % increase in public spending on health leads to increases in inequality by 0.14 % and 0.33 %, respectively.

This relationship may be explained by the fact that such public spending may not be reaching the most disadvantaged socio-economic groups.

Table 5. Regression results of SO2 emissions on health inequality (Fixed Effects).

	Model 1	Model 2	Model 3
Dependent variable	GBDIne	CBDIne	MBDIne
Explanatory variable			
(ln(SO2	(0.063) ***0.44	(0.05) ***0.43	(0.029) 0.017
II	(0.219) ***1.38	(0.06) **0.26	(0.10) ***0.67
(ln(Educ	(0.06) **-0.326	(0.05) ***-0.33	(0.028) ***-0.07
Exp	(0.004) ***0.14	(0.06) ***0.33	(0.0018) 0.005
(ln(GDP	(0.035) ***0.174	(0.03) ***0.012	(0.016) 0.023
(ln(GDP)×ln(SO2	(0.0066) ***-0.044	(0.005) ***-0.04	(0.003) 0.002
R²	0.90	0.91	0.87
Observations	60	60	60

Note: Significance: *** p<0.01, ** p<0.05, * p<0.10. Standard errors in parentheses.

To check the robustness of the results, we studied the relationship between air pollution and health inequalities, using NOx as an alternative pollution indicator to SO2. As we can see, the results of Table.6 for model 4, 5, and 6 are similar to those obtained with the SO2 pollution indicator. However, the impact of NOX on GBD and CBD inequality is greater than the effect of SO2, i.e. a 1 % increase on NOx induce a 0.69 % increase in GBD inequality, and 0.77 % increase in CBD inequality.

Table 6. Regression results of NOx emissions on health inequality (Fixed Effects).

	Model 4	Model 5	Model 6
Dependent variable	GBDIne	CBDIne	MBDIne
Explanatory variable			
(ln(NOx	(0.11) ***0.69	(0.095) ***0.77	(0.046) 0.023
II	(0.25) ***1.54	(0.096) 0.009	(0.103) ***0.65
(ln(Educ	(0.08) ***-0.39	(0.082) **-0.48	(0.01) **-0.083
Exp	(0.004) ***0.13	(0.082) **0.02	(0.017) 0.05
(ln(GDP	(0.051) ***0.25	(0.044) **0.19	(0.021) 0.028
(ln(GDP)×ln(NOx	(0.011) ***-0.072	(0.010) ***-0.076	(0.005) -0.007
R²	0.89	0.88	0.88
Observations	60	60	60

Note: Significance: *** p<0.01, ** p<0.05, * p<0.10. Standard errors in parentheses.

Conclusion and policy implications

Many researchers have studied the impact of pollution on health, but the consequences of pollution on health inequalities have attracted only limited interest to date, and existing studies have focused on China case study. The limited number of studies on health inequalities is mainly explained by the lack of a large database on health outcomes, particularly diseases, specifically at the micro-level.

To fill the gaps of previous research, we developed an econometric model to analyse the relationship between pollution and health inequality over the period 2000 to 2019, taking into account three groups of countries: high-income countries, low- to middle-income countries, and middle- to high-income countries. To measure health inequality, we used the Gini index, based on three different health indicators: overall burden of disease, cardiovascular burden disease and mental burden disease. Health inequality was measured at the level of each group of countries, reflecting health disparities between nations.

The results of our empirical model indicate that pollution, measured in terms of NOx or SO_2 emissions, primarily impacts inequality in global burden disease and inequality in physical health, although its effect on mental health inequality remains unclear. Furthermore, our results suggest that increased healthcare spending alone is not sufficient to reduce health inequalities.

From a policy perspective, our findings suggest that reducing environmental pollution is an effective strategy for improving environmental quality and reducing health inequalities. By treating and mitigating environmental pollution, societies have the potential to reduce the unequal distribution of health outcomes. At the national level, it is recommended that environment ministries implement national pollution control programs and ensure that all sectors comply with them. These policies include improving energy efficiency, whether in the transport, production, or housing sectors. Moreover, ensuring waste management through recycling and waste reduction. Finally, educate the population about the harmful effects of pollution on health, to encourage them to adopt environmentally friendly behavior. These environmental policies should be given priority in programs for lower-middle-income countries, with the aim of combating the negative impact of pollution on health and its distribution.

Moreover, at the national level of these countries, it is recommended to set up effective political institutions to mitigate health inequalities caused by environmental degradation. This could be achieved by establishing universal health care policies and guaranteeing the validity and equitable accessibility to quality health services.

Finally, provide information to people on the negative effects of pollution and providing preventive advice to protect health. In addition to national actions, it is important to take international action to complement the national policies of wealthy countries. These global efforts can be through a massive and rapid transition to wind and solar energy to reduce fuel combustion, and hence ambient air pollution. Moreover, this can be achieved through collaboration between countries through the exchange of knowledge and technology, as well as financial aid, especially from high-income countries to the rest of the world, for the implementation of pollution reduction initiatives. Hence, through environmental policies we'll have a double dividend - fighting pollution and improving health standards.

Despite the consistency of the results obtained in this study, it does have some limitations. Our sample size is small, and we therefore recommend that future studies with data availability for larger number of years on pollution and health indicators to further investigate this relationship. Furthermore, it is recommended to investigate this relationship using a different classification of countries from that of the World Bank, in order to verify the consistence of relationship between pollution and health inequality.

In addition, PM2.5 was proved in previous studies as a detrimental factor to health, it is efficient to study this relationship with data availability of this indicator in future studies. Finally, it is possible to measure health inequality according to socio-economic criteria. Hence, in future studies, we will therefore test the existing relationship between pollution and socio-economic inequality in health.

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Appendix

Appendix A- Country groups

The group of countries are formed as follow:

1. High income countries are : Australia, Austria, Bahamas, Bahrain, Barbados, Belgium, Brunei, Canada, Chile, Croatia, Cyprus, Czechia,

Denmark, Estonia, Finland, France, Germany, Greece, Guyana, Hungary, Iceland, Ireland, Israel, Italy, Japan, Kuwait, Latvia, Lithuania, Luxembourg, Malta, Netherlands, New Zealand, Norway, Oman, Panama, Poland, Portugal, Qatar, Romania, Saudi Arabia, Singapore, Slovakia, Slovenia, South Korea, Spain, Sweden, Switzerland, Trinidad and Tobago, United Arab Emirates, United Kingdom, United States, Uruguay

2. The upper middle income countries are : Albania, Argentina, Armenia, Azerbaijan, Belarus, Belize, Bosnia and Herzegovina, Botswana, Brazil, Bulgaria, China, Colombia, Costa Rica, Dominican Republic, Ecuador, El Salvador, Equatorial Guinea, Fiji, Gabon, Georgia, Guatemala, Indonesia, Jamaica, Kazakhstan, Malaysia, Maldives, Mauritius, Mexico, Moldova, Namibia, North Macedonia, Paraguay, Peru, Russia, Saint Lucia, Saint Vincent and the Grenadines, Serbia, South Africa, Suriname, Thailand, Tonga, Turkey

3. Th low middle income countries are: Algeria, Bangladesh, Benin, Bhutan, Bolivia, Cambodia, Cameroon, Cape Verde, Comoros, Congo, Cote d'Ivoire, Egypt, Eswatini, Ghana, Guinea, Haiti, Honduras, India, Iran, Jordan, Kenya, Kyrgyzs, Cambodia, Cameroon, Cape Verde, Comoros, Congo, Cote d'Ivoire, Egypt, Eswatini, Ghana, Guinea, Haiti, Honduras, India, Iran, Jordan, Kenya, Kyrgyzstan, Laos, Lebanon, Lesotho, Mauritania, Mongolia, Morocco, Myanmar, Nepal, Nicaragua, Nigeria, Pakistan, Papua New Guinea, Philippines, Samoa, Senegal, Solomon Islands, Sri Lanka, Tajikistan, Tanzania, Tunisia, Ukraine, Uzbekistan, Vanuatu, Vietnam, Zambia.

Appendix B- Variable calculations

1. To calculate the weighted average of NOx per capita at level of each group of countries we have used the following equation:

$$NOX = \frac{\sum_{i=1}^{N} Nitrogen\_oxide\_per\_capita_{ij} * Population_{ij}}{\sum Population_{j}} \qquad \text{(Eq. 3)}$$

With N is the number of countries in the group. i is for countries and j for the group of country.

2. We used the same formula applied to the weighted average NOx per capita to calculate the weighted average SO2 per capita.

3. To calculate the average year of schooling we have used the following equation:

$$Educ = \frac{\sum_{i=1}^{N} Average\_year\_of\_schooling}{N} \qquad (Eq.4)$$

4. To calculate the weighted average of GDP per capita we have used the followed equation:

$$GDP = \frac{\sum_{i=1}^{N} Gross_{domestic_{per_{capita}}}{}_{ij} * Population_{ij}}{\sum Population_{j}} \qquad (Eq.5)$$

5. To calculate the weighted average of health expenditure we have used the followed equation:

$$Exp = \frac{\sum_{i=1}^{N} Government\_health\_expenditure_{ij} * GDP_{ij}}{\sum GDP_{j}} \qquad (Eq.6)$$

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