

Indoor and Outdoor Air Pollution and Its Health Impact in Chile

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Abstract. Air pollution poses a significant global health threat, with nearly 99% of the population exposed to levels exceeding WHO recommendations. In Chile, where several cities rank among the most polluted in Latin America, both outdoor air pollution (PM10) and indoor pollution from solid fuel use are major contributors to adverse health outcomes. This study examines the impact of indoor and outdoor air pollution on emergency care visits for respiratory and circulatory diseases using weekly panel data at the municipality level in Chile's most polluted regions. Indoor pollution is proxied by the share of households using solid fuels, while PM10 concentrations represent outdoor exposure. We employ Ordinary Least Squares (OLS) models with fixed effects for year, week, and municipality to control for unobserved heterogeneity and shared shocks. To address potential endogeneity—particularly the link between pollution exposure and socioeconomic disadvantage—we implement a two-stage least squares (2SLS) approach with an instrumental variable. Results indicate that both solid fuel use and PM10 levels are significantly associated with increased emergency visits, especially for respiratory diseases. The study draws on data from national meteorological, air quality, health, and socioeconomic sources. Our findings emphasize the compounded health risks of environmental pollution and underscore the need for targeted interventions in energy policy and public health. By integrating indoor and outdoor pollution sources, this research contributes to a more comprehensive understanding of environmental health burdens and supports progress toward Sustainable Development Goals related to health, clean energy, and inequality reduction.

Keywords: Indoor air pollution · health outcomes · solid fuels · outdoor pollution · household energy sources · Chile

1 Introduction

Globally, 99% of the population is exposed to air pollution levels that exceed World Health Organization (WHO) recommendations, contributing to respiratory diseases, cardiovascular conditions, strokes, and lung cancer. A large percentage of people (2.6 billion), also live with high levels of household indoor air pollution. When combined, these indoor and outdoor pollution effects equate to approximately seven million premature deaths annually (WHO, 2021).

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Air contamination—in particular our exposure to the invisible threat of particulate matter (PM10)—is now recognized as a major threat to human health. When we breathe, such invisible contaminates can penetrate deep into our lungs, reaching the alveoli and absorbing into the blood. Exposure to PM10 contamination can cause multiple dangerous conditions, including inflammation of the lungs, system stress and serious chronic diseases (Kumar et al., 2023; Singh & Rastogi, 2022). Long-term exposure is now closely linked with serious respiratory and cardivascular conditions, as well as incidence of Covid- 19 (Scapini et al., 2023) and neurological dangers such as cognitive decline (Goel & Sen, 2024). As a result, particulate matter has been classified as a carcinogen, and placed within the brackets of other harmful chemicals and emissions such as cigarette smoke (Cui et al., 2015; Raaschou-Nielsen et al., 2016).

Sources of such pollution indoors, for example indoor cooking and heating fuels such as firewood and coal, are also now well documented to have negative effects on health, including higher risks of serious, long term respiratory illness. Vulnerable groups such as the elderly, and children, are particularly at risk to this contamination due to various factors (Guercio et al., 2021; Karottki et al., 2015). Research from various countries, such as Peru and Turkey, confirm the risk and impact of household air pollution on individual and family health, even when socioeconomic and demographic variables are considered (Gajate-Garrido, 2013; Ipek & Ipek, 2021).

In Chile, air pollution remains a critical public health issue. According to IQAir (2022), eight of the fifteen most polluted cities in Latin America are located in Chile, with fine particulate matter levels far exceeding WHO guidelines. These levels are driven by both industrial and transportation emissions, as well as household use of solid fuels. The Chilean National Environmental Survey reports that 32.8% of the population perceives air pollution as the country's most pressing environmental problem, and nearly half live in municipalities with regular or poor air quality. In southern Chile—especially in regions like Maule, Biobío, Ñuble, La Araucanía, Los Ríos, Los Lagos, and Aysén—firewood remains the primary source of energy for heating and, in some cases, for cooking. Firewood combustion accounts for up to 94% of fine particulate matter emissions in cities in these regions (MMA, 2020).

Notably, the health effects of particulate pollution are not uniform across the population. Socioeconomic disparities play a critical role in mediating both exposure and vulnerability. Research from China and the United States has shown that low-income populations experience more severe health consequences from pollution exposure due to factors like neighborhood disadvantage and limited access to health care or cleaner energy alternatives (Lee et al., 2023; Yang et al., 2022). During the COVID-19 pandemic, studies further demonstrated that particulate pollution exacerbated the virus's spread (Scapini et al., 2023), with disproportionate effects on disadvantaged groups (Allen et al., 2021).

This study investigates the health effects of both indoor and outdoor air pollution in Chile, with a focus on respiratory and circulatory diseases. While most existing research tends to focus exclusively on either outdoor pollution or localized case studies of indoor air quality, our analysis integrates both sources of exposure using a panel data approach. We use weekly data at the municipality level, concentrating on some of the most polluted

urban areas in the country, to better understand the acute health impacts of environmental pollution.

Indoor air pollution is proxied by the percentage of households using solid fuels for domestic purposes, while outdoor air pollution is measured by weekly average PM10 concentrations. We estimate the association between these exposures and emergency care visits using linear fixed-effects models that account for unobserved heterogeneity across municipalities and over time. The analysis includes city (municipality), year, and epidemiological week fixed effects to control for time-invariant characteristics and common shocks. To strengthen causal identification and address potential endogeneity—particularly concerns that pollution exposure may be correlated with unobserved determinants of health outcomes—we implement a two-stage least squares (2SLS) approach using accumulated precipitation as an instrument for PM10. This strategy provides robustness to our main findings by offering more credible estimates of the health impacts of air pollution.

This research uses data from the Chilean Meteorological Directorate, the National Air Quality Information System, the Department of Health Statistics of the Ministry of Health, and the CASEN National Income Survey. By highlighting the intersection of environmental conditions, energy access, and health equity in Chile, the study contributes to Sustainable Development Goals (SDGs) 3 (Good Health and Well-Being), 7 (Affordable and Clean Energy), and 10 (Reduced Inequalities).

2 Data Sources

This study examines the effects of meteorological variables, atmospheric pollution, and indoor firewood use on health outcomes by utilizing multiple data sources at the municipal level and by statistical week. The analysis focuses on municipalities with the highest frequency of critical air quality episodes (alerts, pre-emergencies, and environmental emergencies) in 2023, as reported by the Ministry of the Environment. The selected cities include Coyhaique, Temuco, Chillan, Osorno, Talca, Los Angeles, Curico, Rancagua, and Concepcion. Santiago, the capital, is excluded due to its size (it concentrates more than 40% of the country's population) and specific urban characteristics.

The dataset includes weekly information from 2015 to 2022, obtained from publicly available sources, including the Chilean Meteorological Directorate, the National Air Quality Information System, and the Department of Health Statistics of the Ministry of Health. Meteorological data, specifically average temperature and precipitation are retrieved from records maintained by the Chilean Meteorological Directorate (DMC), which operates under the Directorate General of Civil Aeronautics. These records originate from meteorological stations in major cities.

Air pollution data are sourced from monitoring stations of the National Air Quality Information System of the Ministry of the Environment, which measure particulate matter (PM10) concentrations, reported in $\mu g/m^3$.

Health outcome data include emergency care visits, categorized by statistical week and cause. The causes considered are respiratory diseases, circulatory diseases, trauma and poisoning, mental disorders, acute diarrhea, and other conditions. we will focus on respiratory diseases such as such as acute respiratory infections, influenza, pneumonia,

bronchitis, bronchial obstructive crisis, covid-19, among others and circulatory diseases like acute myocardial infarction, stroke, hypertensive crisis and severe arrhythmia. This information is obtained from the Department of Health Statistics and Information (DEIS) of the Ministry of Health.

Energy use data are drawn from the Chilean National Socioeconomic Characterization Survey (CASEN), conducted by the Ministry of Social Development and Family. This analysis uses CASEN survey waves from 2015, 2017, and 2022, which are nationally and regionally representative, and also representative for the major cities included in this study. The survey samples comprise 83,887 households (266,968 individuals) in 2015, 70,948 households (216,439 individuals) in 2017, and 72,056 households (202,231 individuals) in 2022. Starting in 2015, CASEN includes detailed information on the energy sources used for cooking and heating, allowing for the assessment of indoor air pollution exposure. Using this household-level data, we estimate the average use of solid fuels by municipality—the statistical unit of analysis in this study.

The integration of these datasets enables a structured analysis of the relationship between air pollution, meteorological factors, and health outcomes. Descriptive statistics of the sample are in Table 1.

Table 1. Descriptive Statistics

City	Variable	2015	2016	2017	2018	2019	2020	2021	2022
Rancagua	Average solid fuel use %	0.22	0.20	0.19	0.18	0.17	0.16	0.15	0.15
	Respiratory diseases	1,261	1,161	1,156	1,072	1,168	344	440	1,237
	Circulatory diseases	147	116	90	111	131	119	120	126
Curico	Average solid fuel use %	0.60	0.58	0.56	0.55	0.54	0.53	0.51	0.50
	Respiratory diseases	1,372	1,304	1,493	1,492	1,464	278	392	1,460
	Circulatory diseases	79	80	85	88	77	62	66	70
Talca	Average solid fuel use %	0.45	0.42	0.39	0.37	0.35	0.33	0.31	0.29
	Respiratory diseases	2,116	1,850	1,825	1,702	1,655	437	849	2,206
	Circulatory diseases	123	114	122	133	134	109	137	137
Chillan	Average solid fuel use %	0.65	0.65	0.66	0.63	0.61	0.58	0.56	0.54

(*continued*)

Table 1. (*continued*)

City	Variable	2015	2016	2017	2018	2019	2020	2021	2022
	Respiratory diseases	1,162	1,038	1,124	1,156	1,145	243	219	816
	Circulatory diseases	103	97	98	106	127	97	84	93
Concepción	Average solid fuel use %	0.43	0.42	0.41	0.41	0.40	0.40	0.39	0.39
	Respiratory diseases	1,621	1,475	1,543	1,553	1,624	326	353	1,339
	Circulatory diseases	107	94	74	105	138	108	114	125
Los Angeles	Average solid fuel use %	0.82	0.81	0.81	0.79	0.78	0.77	0.76	0.74
	Respiratory diseases	2,060	2,014	2,051	1,891	1,633	400	263	1,193
	Circulatory diseases	176	163	169	193	203	163	151	142
Temuco	Average solid fuel use %	0.75	0.74	0.74	0.73	0.71	0.70	0.69	0.68
	Respiratory diseases	1,027	937	914	927	887	222	510	1,497
	Circulatory diseases	116	109	110	111	91	75	114	105
Osorno	Average solid fuel use %	0.91	0.89	0.87	0.85	0.83	0.81	0.78	0.76
	Respiratory diseases	1,429	1,378	1,345	1,312	1,249	274	254	969
	Circulatory diseases	76	73	72	79	90	82	76	80
Coyhaique	Average solid fuel use %	0.93	0.90	0.86	0.84	0.83	0.82	0.80	0.79
	Respiratory diseases	458	425	443	417	395	85	90	329
	Circulatory diseases	28	33	27	26	27	23	25	31

Note: Respiratory and circulatory diseases refer to the weekly average number of emergency care visits related to these conditions.

3 Methodology

Our hypothesis is that higher use of solid fuels at the household level contributes to increased indoor air pollution, which in turn may be associated with a greater burden of respiratory and circulatory diseases. To assess this relationship, we estimate panel data models using weekly information at the municipality level. The dependent variables are emergency care visits for (1) respiratory diseases and (2) circulatory diseases. Explanatory variables include: (a) the percentage of households in the municipality using solid fuels for domestic purposes as a proxy for indoor air pollution; (b) outdoor air pollution indicator (PM10); and (c) average weekly temperature. This approach allows us to capture both indoor and outdoor environmental influences on acute health outcomes across time and space.

The stochastic model to be estimated is specified to examine the relationship between geographical variables and health indicators by cause and age group. The econometric model is formulated as follows:

$$y_{it} = f(MP10_{it}, CS_{it}, T_{it}) \tag{1}$$

where:

y_{it}: Number of emergency care services, worked in logarithmic scale, at municipality i at week t

CS_{it}: Is an indicator showing the proportion of dwellings that use solid fuels inside the home, at municipality i at week t

$MP10_{it}$: Atmospheric pollution, average concentration level of particulate matter PM10, at municipality i at week t

T_{it}: : Average ambient temperature (°C), at municipality i at week t

The first preliminary stochastic model corresponds to a fixed effects specification (2), estimated under the assumption that error variances may be heteroscedastic. To account for this, we employ robust standard errors, which allow consistent estimation of standard errors even in the presence of unknown heteroscedasticity.

$$y_{it} = \beta_0 + \beta_1 CS_{it} + \beta_2 MP10_{it} + \beta_3 T_{it} + v_{it} + \varepsilon_{it}, \tag{2}$$

$$\varepsilon_{it} \sim N\left(0, \sigma_{it}^2\right); Cov\left(\varepsilon_{it}, \varepsilon_{jt}\right) = 0; i \neq j; t \neq s \tag{3}$$

We include fixed effects in the model to improve identification and control for unobserved heterogeneity across municipalities and over time. Specifically, the estimation incorporates city fixed effects to capture time-invariant characteristics such as baseline infrastructure, geographic conditions, or long-term socioeconomic factors that could influence both pollution levels and health outcomes. Additionally, we include week fixed effects to account for national shocks, seasonal variation, and trends affecting all municipalities simultaneously, such as influenza outbreaks or national policy changes. The fixed effects specification allows us to isolate within-city variation over time, thus strengthening the causal interpretation of the estimated parameters.

To address potential endogeneity in the pollution variable—particularly the concern that more polluted areas may be systematically associated with lower-income populations and worse baseline health outcomes—we implement a two-stage least squares

(2SLS) estimation strategy. Accumulated precipitation is used as an instrumental variable (IV) for PM10 concentrations, based on its strong negative correlation with pollution levels and its assumed exogeneity with respect to health outcomes. In the first stage, predicted values of PM10 are obtained from a regression on the instrument and control variables. These fitted values are then used in the second stage as regressors in the main equation, estimating the impact of pollution on emergency care visits. This approach improves causal identification and provides more reliable estimates of the health effects of air pollution.

4 Results

The baseline specification is a fixed-effects model estimated using robust standard errors to account for potential violations of the homoscedasticity assumption. This model includes fixed effects for city, year, and epidemiological month, which control for time-invariant differences across municipalities as well as shared temporal shocks. Given the structure of the data and the rejection of the random effects specification based on the Hausman test, fixed effects were preferred to ensure more reliable estimates.

Table 2 presents the results from two fixed-effects specifications for weekly emergency visits due to respiratory and circulatory diseases. The first pair of columns examines the association between total household solid fuel use (across cooking, heating, and water heating) and emergency visits. The second pair of columns isolates the effect of solid fuel use specifically for heating purposes.

In both sets of models, solid fuel use is positively and significantly associated with emergency visits. A 10-percentage-point increase in the share of households using solid fuels for any purpose is associated with a 16.38% increase in respiratory emergency visits and an 8.69% increase in circulatory visits per week. When the analysis focuses solely on solid fuel use for heating, the estimated effects are even larger: a 10-percentage-point increase is associated with a 21.15% increase in respiratory visits and an 11.76% increase in circulatory visits. These findings confirm that indoor air pollution—particularly from heating with solid fuels—is a strong contributor to acute health outcomes, with respiratory conditions being more sensitive than circulatory ones.

The R-squared values (0.783 for respiratory and 0.85 for circulatory conditions) indicate a strong model fit in both cases, particularly for circulatory diseases. These results suggest that the included covariates—such as solid fuel use, PM10 levels, and temperature—explain a large proportion of the variation in weekly emergency visits.

Additional covariates yield meaningful effects. PM10 levels are positively and significantly associated with both respiratory and circulatory conditions, reinforcing the importance of outdoor air pollution as a driver of acute illness. In contrast, temperature is positively associated only with respiratory visits, suggesting that environmental stress—likely from extreme heat or cold—may trigger respiratory issues. At the same time, no significant association is found with circulatory emergencies.

Overall, the results show that indoor and outdoor air pollution substantially affects population health. The stronger effects observed for respiratory conditions are consistent with biological mechanisms, as particulate matter more directly and immediately impacts respiratory tissues.

Table 2. Linear fixed effects regression results - air pollution and weekly emergency visits by type of disease

	Respiratory diseases (log) Model (1)	Circulatory diseases (log) Model (2)	Respiratory diseases (log) Model (3)	Circulatory diseases (log) Model (4)
MP10	0.00160***	0.000433***	0.00160***	0.000434***
	(0.00031)	(0.00017)	(0.00031)	(0.00017)
% of solid fuel consumption	1.638***	0.869***		
	(0.42700)	(0.25100)		
% of solid fuel consumption for heating			2.072***	1.176***
			(0.41300)	(0.24600)
Average atmospheric temperature	0.0114**	-0.00257	0.0115**	-0.00254
	(0.00463)	(0.00202)	(0.00462)	(0.00202)
Constant	6.212***	4.660***	6.119***	4.593***
	(0.15100)	(0.07950)	(0.14800)	(0.07820)
City/year/month fixed effects	Yes	Yes	Yes	Yes
Observations	3,744	3,744	3,744	3,744
R-squared	0.783	0.850	0.783	0.850

Note: Respiratory and circulatory diseases refer to the weekly average number of emergency care visits related to these conditions. Robust standard errors in parentheses. Significance level: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$
Source: Own elaboration

To address potential endogeneity in air pollution exposure—particularly the possibility that more polluted areas tend to coincide with lower-income populations and worse baseline health outcomes—we estimate a two-stage least squares (2SLS) model. Accumulated precipitation is used as an instrumental variable for PM10 concentrations, based on its strong negative correlation with pollution levels and its assumed exogeneity with respect to emergency health outcomes. The first stage of the model, along with tests of instrument strength and endogeneity, are reported in the appendix (Tables A1 and A2). These tests confirm the relevance of the instrument and suggest that endogeneity is present and statistically significant in the models using solid fuel for heating. At the same time, evidence is suggestive but inconclusive for models using total solid fuel consumption.

Table 2 presents the results of the second stage of the 2SLS estimation. All models include fixed effects for city, year, and epidemiological month, and are estimated using robust standard errors to account for heteroscedasticity. Model (IV1) and (IV2) report estimates using total household solid fuel consumption, while Model (IV3) and (IV4) focus on solid fuel use specifically for heating purposes.

Table 3. 2SLS Fixed effects estimates - Impact of PM10 and household solid fuel use on emergency visits for respiratory and circulatory diseases

	Respiratory diseases (log) Model (IV1)	Circulatory diseases (log) Model (IV2)	Respiratory diseases (log) Model (IV3)	Circulatory diseases (log) Model (IV4)
MP10	0.00334***	0.00123**	0.00338***	0.00126**
	(0.00109)	(0.00053)	(0.00108)	(0.00053)
% of solid fuel consumption	1.617***	0.859***		
	(0.42800)	(0.24900)		
% of solid fuel consumption for heating			2.062***	1.171***
			(0.41300)	(0.24500)
Average atmospheric temperature	0.0145***	−0.00115	0.0147***	−0.00107
	(0.00493)	(0.00222)	(0.00492)	(0.00222)
Constant	6.079***	4.599***	5.981***	4.529***
	(0.16700)	(0.08950)	(0.16500)	(0.08880)
City/year/month fixed effects	Yes	Yes	Yes	Yes
Observations	3,744	3,744	3,744	3,744
R-squared	0.781	0.849	0.781	0.849

Note: Respiratory and circulatory diseases refer to the weekly average number of emergency care visits related to these conditions. Robust standard errors in parentheses. Significance level: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.
Source: Own elaboration.

The results confirm a strong and statistically significant association between PM10 concentrations and emergency visits for both respiratory and circulatory conditions. A one-unit increase in PM10 is associated with a 0.33% increase in respiratory visits ($p < 0.01$) and a 0.12% increase in circulatory visits ($p < 0.05$). These effects are larger than those obtained under OLS, suggesting that models not accounting for endogeneity may underestimate the true health impacts of air pollution.

Regarding indoor pollution, a 10-percentage-point increase in the share of households using solid fuels for any domestic purpose is associated with a 16.17% increase in emergency visits for respiratory conditions and an 8.59% increase for circulatory conditions. When restricting the analysis to solid fuel use for heating only, the estimated effects are stronger: 20.62% and 11.71% increases in respiratory and circulatory emergencies, respectively. These findings highlight the health burden imposed by indoor heating practices involving solid fuels.

The average atmospheric temperature is also positively associated with respiratory emergencies across all specifications, possibly reflecting the role of extreme temperatures

in exacerbating respiratory conditions. No statistically significant association is found between temperature and circulatory visits.

Overall, these results reinforce the conclusion that both outdoor and indoor sources of air pollution significantly affect acute health outcomes, especially for respiratory diseases. The use of an instrumental variable strengthens the causal interpretation of these relationships, particularly in the models focused on indoor heating.

5 Discussion

Our findings confirm that both air pollution and indoor pollution resulting from the use of fossil fuels for heating and cooking, as well as temperature, have a strong and statistically significant impact on city-level health outcomes. These results are consistent with previous studies that have linked outdoor pollution and cardiovascular and respiratory diseases on the one hand (Kumar et al., 2023; Singh & Rastogi, 2022; Scapini et al., 2023; Goel & Sen, 2024), and on the other hand, previous studies that have linked solid fuel use to higher risks of cardiovascular and respiratory diseases (Gajate-Garrido, 2013; Goel & Sen, 2024; Kumar et al., 2023; Lee et al., 2023; Ipek & Ipek, 2021; Singh & Rastogi, 2022). For example, studies by Guercio et al. (2021) and Karottki et al. (2015), demonstrate an increased risk of chronic respiratory diseases associated with the use of solid fuels for heating, particularly among vulnerable groups.

Our results provide evidence of the need to design public health interventions that specifically address both indoor air quality—particularly that associated with the use of solid fuels for heating—and outdoor air pollution. In this regard, the findings underscore the importance of promoting policies aimed at mitigating these risks, especially in the areas most affected by pollution in Chile, as documented in air quality studies of cities such as Coyhaique and Temuco (MMA, 2020).

Furthermore, this study aligns with existing evidence that highlights the role socioeconomic conditions play in determining levels of exposure to air pollution. Previous research indicates that lower-income populations are more exposed due to limited access to cleaner energy sources and the widespread use of solid fuels for home heating (Yang et al., 2022).

To account for spatially varying but time-invariant factors such as socioeconomic conditions, we include city-level fixed effects in our models. In addition, to address potential endogeneity in outdoor air pollution—arising, for example, from reverse causality or omitted variables—we implement an instrumental variable approach. This strategy strengthens the causal interpretation of our estimates and confirms that both indoor and outdoor pollution are significantly associated with adverse population health outcomes.

A key limitation of this study is the absence of direct measurements of indoor air pollution. Instead, we use the proportion of households relying on solid fuels as a proxy, extrapolating this variable for years in which direct data were unavailable. While this approach enables a partial estimation of exposure to indoor pollution, it may not fully capture the actual magnitude of the problem.

6 Conclusion

This study provides robust empirical evidence that both indoor and outdoor air pollution significantly affect health outcomes in Chile's most polluted cities. Exposure to particulate matter is strongly associated with increased emergency care visits for respiratory and cardiovascular conditions. The use of solid fuels for indoor heating, in particular, emerges as a key driver of these adverse effects, underscoring the importance of monitoring and addressing indoor air quality alongside ambient pollution levels.

The findings point to the need for public health responses considering environmental exposures occurring within households, not just in urban outdoor environments. The analysis strengthens causal inference by employing an instrumental variable strategy and municipality-level fixed effects and confirms that air pollution, regardless of its source, contributes to acute health burdens.

Rather than reiterating broad calls for clean energy transitions, the results support the implementation of targeted, evidence-based interventions to reduce reliance on solid fuels and improve energy efficiency at the household level. The positive and statistically significant association between indoor air pollution and emergency room visits for respiratory and circulatory conditions reinforces this need. As emphasized in international literature (Kumar et al., 2023; Singh & Rastogi, 2022), replacing solid fuels with cleaner alternatives improves air quality, reduces harmful emissions, contributes to climate change mitigation, and enhances public health.

Finally, addressing the health impacts of air pollution requires intersectoral coordination across energy, health, and economic development policies, along with implementation across multiple levels of governance—national, regional, and municipal. Future research should expand geographic coverage and incorporate variables such as housing materials, certified fuel use, and policy instruments like energy subsidies to better inform these multisectoral strategies.

Appendix

Table A1. First-Stage Regression Results - Dependent variable: PromMP10 (mean particulate matter 10μm)

	MP10	MP10
Total precipitation	−0.295***	−0.295***
	(0.0180)	(0.0180)
% of solid fuel consumption	35.35	
	(28.3800)	
% of solid fuel consumption for heating		27.25
		(27.4000)

(*continued*)

Table A1. (*continued*)

	MP10	MP10
Average atmospheric temperature	−1.469***	−1.468***
	(0.2660)	(0.2660)
Constant	65.78***	67.75***
	(9.0680)	(8.7870)
City/year/month fixed effects	Yes	Yes
Observations	3,744	3,744
R-squared	0.52	0.52

Note: Instrument Total precipitation. Robust standard errors in parentheses. Significance level: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$
Source: Own elaboration

Table A2. Tests for Endogeneity of PromMP10

	Test	Statistic	p-value
Model (1)	Durbin (χ^2)	2.8916	0.0890
	Wu-Hausman (F)	2.8198	0.0932
Model (2)	Durbin (χ^2)	2.4592	0.1168
	Wu-Hausman (F)	2.3622	0.1244
Model (3)	Durbin (χ^2)	3.0125	0.0826
	Wu-Hausman (F)	2.9377	0.0866
Model (4)	Durbin (χ^2)	2.6255	0.1052
	Wu-Hausman (F)	2.5206	0.1125

Note: Endogeneity tests for *PromMP10* using the Durbin and Wu–Hausman statistics. The null hypothesis is that *PromMP10* is exogenous. Although none of the tests reject the null at the 1% level, some models (e.g., Model 3) show p-values below 10%, suggesting potential endogeneity concerns. The instrumental variable approach is therefore used as a robustness check to account for possible bias from omitted variables or reverse causality.Source: Own elaboration

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