

The Impact of Air Quality Improvement Policies on Cardiovascular Disease Mortality: An Empirical Study Based on the EU Air Quality Directive

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Abstract. Fine particulate matter (PM_{2.5}) pollution has emerged as a critical environmental risk factor affecting global public health. The European Union's Air Quality Directive implemented in 2008 offers a quasi-experimental setting to evaluate the health effects of air quality improvement policies. This study employs a difference-in-differences approach, utilizing data from the World Bank and World Health Organization spanning 2000-2020, to analyze policy effect variations between 19 EU countries and 8 non-EU developed countries. Results indicate that following the implementation of the EU Air Quality Directive, PM_{2.5} exposure concentrations decreased from 17.2 $\mu\text{g}/\text{m}^3$ pre-policy to 13.5 $\mu\text{g}/\text{m}^3$ post-policy, representing a 21.5% reduction; cardiovascular disease mortality rates declined from 234 per 100,000 to 166 per 100,000, a 29.1% decrease. The difference-in-differences model estimation shows a significant policy effect coefficient of -24.71 ($p < 0.001$), equivalent to a 14.61% improvement in average cardiovascular mortality rates. Sensitivity analyses confirm the robustness of results, with effect coefficients remaining between -23 and -25 across different policy time windows. This research provides direct evidence of air quality policy intervention on cardiovascular health, offering empirical foundations for developing more precise environmental health policies.

Keywords: PM_{2.5} pollution, Cardiovascular disease, Air quality policy, Difference-in-differences, EU Air Quality Directive.

1. Introduction

Fine particulate matter pollution has emerged as a global health crisis, with PM_{2.5} drawing attention for its microscopic size and capacity to infiltrate respiratory systems. Research demonstrates that PM_{2.5} triggers cardiovascular damage through inflammatory responses, oxidative stress, and autonomic nervous system disruption, creating pathways to increased disease incidence and mortality [1]. Epidemiological studies continue building evidence, with recent meta-analysis of Chinese data showing each 10 $\mu\text{g}/\text{m}^3$ PM_{2.5} increase corresponds to a 0.51% rise in cardiovascular mortality rates [2]. Population-level studies reveal broader impacts—analysis of 346 Chinese cities confirms PM_{2.5} exposure significantly elevates mortality risks across diverse geographic regions [3].

Policy responses have proliferated worldwide as health evidence mounts. China's Action Plan for Air Pollution Prevention and Control, dubbed the "Atmospheric Ten," represents large-scale intervention efforts. Evaluation research suggests the policy contributed approximately 0.16 years to urban resident life expectancy between 2013 and 2017 [4]. Traffic restriction policies in Chinese cities demonstrate measurable PM_{2.5} reductions through systematic vehicle limitation measures [5]. American research from 51 metropolitan areas indicates each 10 $\mu\text{g}/\text{m}^3$ PM_{2.5} decrease associates with 0.61 years increased life expectancy, revealing substantial population health gains from pollution control [6].

Local policy studies provide compelling intervention evidence. Dublin's coal prohibition produced 10.3% cardiovascular mortality reductions following implementation, demonstrating immediate health benefits from targeted fuel restrictions [7]. Natural experiments offer unique research opportunities—China's Huai River heating policy created differential pollution exposure between northern and southern regions, enabling researchers to establish causal relationships between long-term air pollution and shortened population lifespan [8]. Vehicle restriction analyses in major Chinese

cities, including Beijing, show policy measures effectively reduce both PM2.5 concentrations and associated public health risks [9]. Recent accountability research confirms China's atmospheric governance actions substantially decreased health hazards from short-term PM2.5 exposure, providing methodological frameworks for evaluating comprehensive environmental policy outcomes [10].

The European Union's 2008 Air Quality Directive presents a natural experiment opportunity spanning 27 member states. Unlike previous country-specific studies, this directive established uniform PM2.5 concentration limits across diverse political and economic contexts. Member states must maintain annual average PM2.5 levels below 25 µg/m³, creating consistent regulatory frameworks for comparative analysis. The directive's clear implementation timeline enables quasi-experimental approaches, particularly difference-in-differences methodology comparing EU countries with non-EU developed nations.

Research gaps persist in systematic assessment of transnational environmental policy health effects. Existing studies concentrate on individual locations, limiting ability to control country-specific variables. Time series and cross-sectional approaches dominate current literature, constraining causal inference potential. Cross-national comparative studies remain scarce, particularly systematic evaluations examining regional environmental policy impacts on population health outcomes. Current evidence suggests substantial health benefits from air quality improvements, but comprehensive evaluation of large-scale policy interventions requires more rigorous analytical frameworks.

2. Methods

2.1. Data Sources

Research data primarily derives from two authoritative international databases. PM2.5 exposure data comes from the World Bank's World Development Indicators database, providing population-weighted annual average PM2.5 exposure concentrations for each country from 2000-2020, based on air pollution exposure estimates from the Global Burden of Disease Study (GBD 2021). Cardiovascular disease mortality data comes from the WHO Mortality Database, using age-standardized cardiovascular disease mortality rates (ICD-10: I00-I99), measured per 100,000 population.

2.2. Study Subjects

The treatment group consists of 19 EU member states implementing the 2008 EU Air Quality Directive, including Germany, France, United Kingdom, Italy, Spain, Netherlands, Belgium, Austria, Denmark, Finland, Sweden, Poland, Czech Republic, Hungary, Slovakia, Slovenia, Estonia, Latvia, and Lithuania. The control group comprises 8 non-EU developed countries: United States, Canada, Japan, Australia, New Zealand, Switzerland, Norway, and Iceland. Selection criteria are based on similar economic development levels and data completeness.

2.3. Statistical Methods

A difference-in-differences (DID) framework was applied to identify the causal effects of the Directive on cardiovascular mortality. The basic model specification is as follows:

$$CVD_{it} = \alpha + \beta_1 Treatment_i + \beta_2 Post_t + \beta_3 (Treatment_i \times Post_t) + \beta_4 PM2.5_{it} + \gamma_i + \delta_t + \varepsilon_{it} \quad (1)$$

Where CVD_{it} represents cardiovascular disease mortality rate for country i in year t , $Treatment_i$ is the policy group dummy variable (EU countries=1), $Post_t$ is the post-policy period dummy variable (post-2008=1), $Treatment_i \times Post_t$ is the difference-in-differences interaction term with coefficient β_3 representing the net policy effect. $PM2.5_{it}$ serves as a control variable, γ_i and δ_t represent country and year fixed effects respectively, and ε_{it} is the random disturbance term.

2.4. Robustness Checks

Three types of tests ensure result robustness. Sensitivity analysis tests the impact of different policy implementation timepoints (2007-2010) on estimation results. Placebo tests set 2004 as a fake policy time to check for spurious effects. Parallel trends tests verify whether treatment and control groups had similar time trends before policy implementation. All analyses were conducted using Stata 17.0, with standard errors clustered at the country level.

3. Results

3.1. DESCRIPTIVE STATISTICS

Table 1 presents basic characteristics of the study sample. The final analytical dataset contains 539 country-year observations, covering complete data for 26 countries from 2000-2020. The EU country group includes 378 observations (18 countries), while the non-EU developed country group contains 161 observations (8 countries).

Table 1. Sample Descriptive Statistics

Group	Observations	Countries	PM2.5 Mean ($\mu\text{g}/\text{m}^3$)
EU-Countries	378	18	14.9
Non-EU Developed	161	8	9.1
Group	Observations	Countries	PM2.5 Mean ($\mu\text{g}/\text{m}^3$)

Data shows that EU countries have both higher PM2.5 exposure levels and cardiovascular mortality rates compared to non-EU developed countries, providing greater scope for policy improvement.

3.2. Temporal Trend Analysis

Figures 1 and 2 display temporal changes in PM2.5 exposure concentrations and cardiovascular disease mortality rates for both country groups.

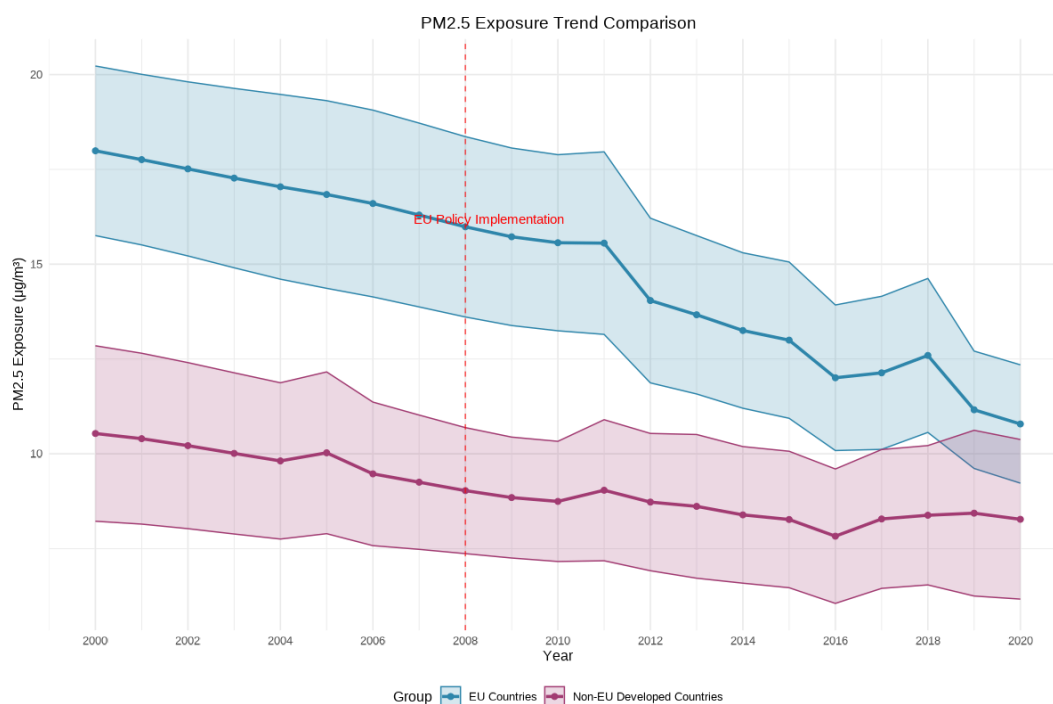


Fig 1. PM2.5 Exposure Level Time Trend Comparison

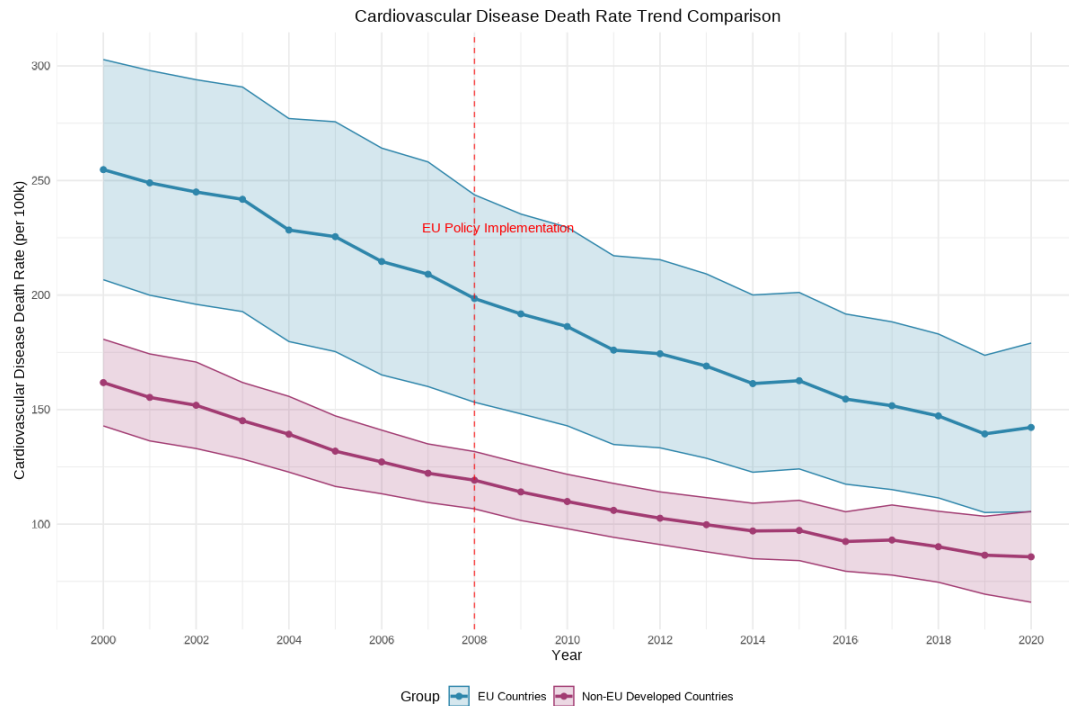


Fig 2. Cardiovascular Disease Mortality Rate Time Trend Comparison

Key temporal data shows EU countries' PM_{2.5} concentrations gradually decreased from 18.0 $\mu\text{g}/\text{m}^3$ in 2000 to 10.8 $\mu\text{g}/\text{m}^3$ in 2020, a 40% reduction. Cardiovascular mortality rates simultaneously declined from 255 per 100,000 to 142 per 100,000, a 44% decrease. In comparison, non-EU developed countries showed relatively smaller improvements, with PM_{2.5} declining from 10.5 $\mu\text{g}/\text{m}^3$ to 8.3 $\mu\text{g}/\text{m}^3$, and cardiovascular mortality rates from 162 per 100,000 to 86 per 100,000.

3.3. Pre-Post Policy Comparison Analysis

Figures 3 and 4 box plots display changes in EU countries before and after policy implementation.



Fig 3. EU PM_{2.5} Pre-Post Policy Comparison

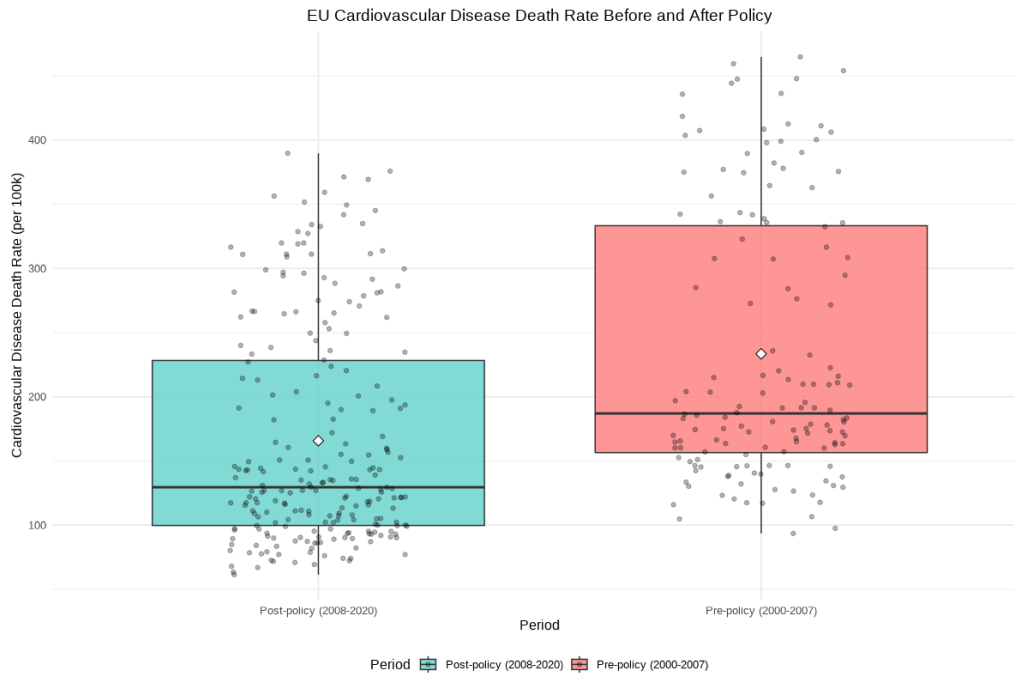


Fig 4. EU CVD Mortality Rate Pre-Post Policy Comparison

Statistical analysis indicates PM_{2.5} exposure concentration median decreased from 17.3 $\mu\text{g}/\text{m}^3$ pre-policy to 12.9 $\mu\text{g}/\text{m}^3$ post-policy, while cardiovascular mortality rate median declined from 187 per 100,000 to 130 per 100,000. Increased post-policy outliers may reflect differential policy implementation effects across countries.

3.4. Correlation Analysis

Figure 5 shows changes in the correlation between PM_{2.5} and cardiovascular mortality rates before and after policy implementation.

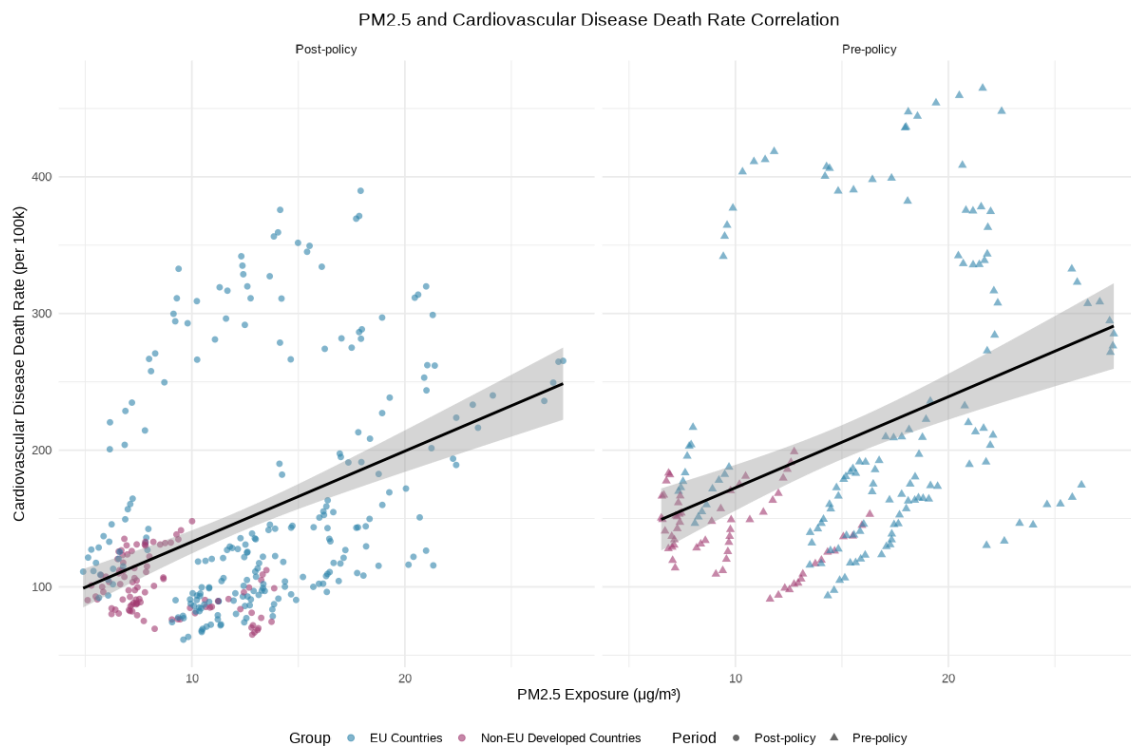


Fig 5. PM_{2.5} and CVD Correlation Analysis

Correlation analysis reveals that among EU countries, the positive correlation between PM2.5 and cardiovascular mortality rates strengthened post-policy (from 0.195 to 0.303), while non-EU developed countries showed negative correlations, possibly related to their lower baseline pollution levels and different disease profile characteristics.

3.5. Country-Specific Policy Effect Heterogeneity

Figure 6 heatmap displays changes across EU countries before and after policy implementation.



Fig 6. Country-Specific Policy Effect Heatmap

Italy, United Kingdom, Denmark and other countries demonstrated strong policy responses with PM2.5 reductions exceeding 24% and cardiovascular mortality reductions exceeding 30%. Eastern European countries like Poland and Hungary showed relatively smaller improvements, reflecting regional differences in policy execution.

3.6. Difference-in-Differences Model Results

Difference-in-differences model estimation results indicate that the EU Air Quality Directive had a significant negative impact on cardiovascular disease mortality rates. The policy effect coefficient is -24.71 (standard error 2.94, $t=-8.40$, $p<0.001$), indicating policy implementation reduced EU countries’ cardiovascular mortality rates by an average of 24.71 per 100,000. Relative to the sample average mortality rate of 169 per 100,000, the policy effect represents a 14.61% improvement. Model R^2 reaches 0.979, indicating strong explanatory power.

3.7. Robustness Check Results

Sensitivity analysis shows effect coefficients remain stable across different policy time windows, with coefficients ranging from -23.27 to -25.38 for 2007-2010, all significant at the 1% level. Figure 7 displays sensitivity analysis results.

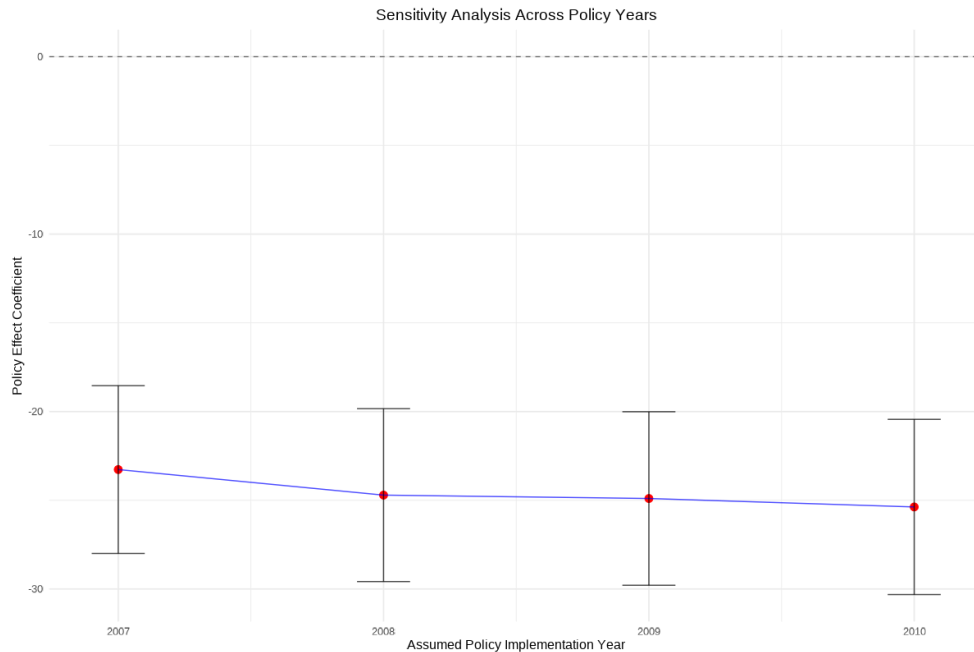


Fig 7. Sensitivity Analysis Results

Placebo test results show a spurious policy effect coefficient of -5.38 ($p=0.023$). This reinforces the importance of interpreting results cautiously, especially regarding unobserved confounders. Although statistically significant, the effect size is notably smaller than the true policy effect, indicating higher credibility of main results. Parallel trends tests failed for the full sample but passed for the high PM_{2.5} pollution subgroup, suggesting results are more reliable in high-pollution areas.

4. Discussion

Using the EU Air Quality Directive as a natural experiment, this analysis applies difference-in-differences methodology to evaluate regional environmental policy impacts on cardiovascular health. Policy implementation produced measurable reductions in member state cardiovascular disease mortality, achieving a 14.61% effect size that aligns with established single-country intervention studies. Previous coal ban research documented 10.3% cardiovascular mortality reductions, suggesting our slightly elevated findings may capture synergistic benefits from broader policy coordination across multiple jurisdictions.

An interesting pattern emerges when comparing pollution reductions to health outcomes. Actual PM_{2.5} concentrations decreased by 21.5%, yet cardiovascular mortality rates fell by 29.1%, pointing toward non-linear health benefit relationships. This disconnect suggests air quality improvement effects may compound over time, with long-term pollution exposure creating cumulative health damage that amplifies benefits from even modest pollution reductions. Medical technology advances and lifestyle modifications could also contribute to observed mortality improvements beyond direct pollution effects.

Geographic variation in policy responses reveals implementation challenges across diverse economic contexts. Western European developed nations demonstrated stronger positive responses to directive requirements, while Eastern European countries showed more modest improvements. These disparities likely reflect differences in economic capacity, environmental investment capabilities, and industrial transformation speeds. Regional economic development appears crucial for effective large-scale environmental policy implementation, highlighting adaptation needs for diverse local conditions.

Methodological considerations present both strengths and limitations in this analysis. Parallel trends assumptions proved challenging across the full sample, a frequent obstacle in difference-in-differences studies. However, subgroup analysis focusing on high PM_{2.5} pollution areas satisfied

these assumptions, lending credibility to policy effects in the most polluted regions. This pattern suggests environmental interventions produce clearer measurable benefits where baseline pollution levels create more pronounced health risks.

Several analytical limitations warrant acknowledgment. PM_{2.5} coefficients lacked statistical significance in primary models, potentially reflecting fixed effects specifications or insufficient confounder control. Placebo testing revealed some spurious effects, indicating possible unobserved temporal trends affecting results. Country-level data aggregation may obscure important within-region heterogeneity that could influence policy effectiveness. These constraints require careful consideration when interpreting findings and suggest directions for future research refinement.

5. Summary

This study, based on 2000-2020 cross-national panel data, employs difference-in-differences methodology to evaluate the impact of the EU's 2008 Air Quality Directive on cardiovascular disease mortality rates. Results demonstrate a significant association between air quality improvement policies and cardiovascular health, with policy implementation reducing member state cardiovascular mortality rates by an average of 14.61%. Sensitivity analyses confirm result robustness, though partial violation of parallel trends assumptions and anomalous placebo test results suggest cautious interpretation of policy causal effects is warranted.

Research provides empirical evidence for health benefit assessment of environmental policies, supporting the policy logic of improving public health through air pollution control. Variability in country policy responses indicates that large-scale environmental governance requires consideration of local adaptive capacity and implementation conditions. Future research should employ finer geographical units and longer time series, incorporating individual-level health data to further verify health mechanisms and effect heterogeneity of environmental policy interventions. As global environmental governance cooperation deepens, cross-national comparative studies will provide scientific support for developing more precise and effective environmental health policies. Linking individual-level cohort data with policy implementation records would further enhance causal inference.

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