Regional Heterogeneity in the Joint Effects of Ambient Air Pollution Mixtures on Allergic Rhinitis Among Four-Year-Old Children in Taiwan: A Quantile G-Computation Approach

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Abstract

Background and Objectives: In environmental epidemiology, young children are inevitably exposed to complex multi-pollutant mixtures. Traditional single-pollutant models often suffer from severe multicollinearity, while conventional mixture approaches like Weighted Quantile Sum (WQS) regression fail when pollutants exhibit opposing directions of health effects. This study aims to evaluate the joint causal effects of ambient air pollution mixtures on allergic rhinitis (including clinical diagnosis and long-term medication use) among four-year-old children in Taiwan, with a specific focus on identifying regional heterogeneities across Northern, Central, and Southern areas.

Methods: Data were derived from the 7th wave of the Kids in Taiwan study (KIT), tracking 6,193 four-year-old singletons. To robustly handle highly correlated air pollutants that potentially possess both hazardous and compensatory effects, we implemented Quantile g-computation (qgcomp), an innovative statistical framework proposed by Keil et al. (2020) to yield unbiased joint estimates. The exposure mixture comprised fine particulate matter ($PM_{2.5}$), ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and carbon monoxide (CO). Multivariable models were adjusted for child sex, maternal/paternal smoking, general health status, sleep quality, outdoor space accessibility, dietary habits, prematurity, low birth weight, and caregiving types.

Results: The qgcomp analysis revealed a statistically significant positive joint effect (ψ) of the multi-pollutant mixture on child allergic rhinitis exclusively in the Northern region (ψ = 0.292, P = 0.034; Relative Risk (RR)=1.35, 95% CI: 1.02 to 1.75). This indicates that a simultaneous one-quantile increase in all air pollutants significantly elevates the risk of allergic rhinitis among children in Northern Taiwan. The net joint effects for the total sample (ψ = 0.097, P = 0.360; RR=1.1), Central region ψ = -0.041, P = 0.817; RR=0.96), and Southern region (ψ = -0.009, P = 0.950; RR=0.99) did not reach statistical significance.

Crucially, decomposing the positive weight profiles unveiled a striking structural shift across regions. Nitrogen dioxide (NO_2) emerged as the predominant risk driver across all models, contributing 69.38% in the total sample, 50.63% in the Northern, 88.81% in the Central, and 57.02% in the Southern regions, underscoring the ubiquitous threat of traffic-related urban emissions. Conversely, a distinct environmental profile was observed in the Southern region, where the hazardous weight of $PM_{2.5}$ sharply escalated to 33.01%, markedly outstripping its impact in the North (5.84%). Covariate analysis consistently showed that male sex, poor general health, and impaired sleep quality were robustly associated with an increased risk of allergic rhinitis across all regional models ($P < 0.001$).

Conclusions: Our study provides compelling empirical evidence that multi-pollutant mixtures exert region-specific impacts on child respiratory health in Taiwan. While traffic-derived NO_2 serves as the baseline environmental driver nationwide, children in the Southern region face an intensified, secondary "particulate-driven" threat from $PM_{2.5}$. Although the net joint effect in the Southern region was non-significant—potentially due to compromised statistical power from a smaller sample size (n = 1,400) or compensatory gas interactions—the pronounced structural combination of high NO_2 and escalated $PM_{2.5}$ weights underscores critical geographical specificity. Utilizing qgcomp successfully bypassed traditional statistical bottlenecks, offering localized, precision-driven scientific evidence that underscores the need for combining nationwide traffic emission controls with region-specific industrial particulate regulations.

Keywords: Allergic Rhinitis, Air Pollution Mixture, Quantile G-Computation, Regional Heterogeneity, $PM_{2.5}$, NO_2, Pediatric Health