Precision Public Health Approach to Chronic PM2.5 Exposure

by Hari Krismanuel

Precision Public Health Approach to Chronic $PM_{2.5}$ Exposure: A Natural Experiment on Pulmonary Function Among Older Adults Across High-Contrast Gradients

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ABSTRACT

Background: While $PM_{2.5}$ is a known respiratory hazard, most studies lack the temporal depth to distinguish chronic impacts from acute effects, particularly among vulnerable older adults. Addressing the inherent limitations of standard cross-sectional surveys, this study employs a **pioneering natural experiment design** with a 10-year stable residency filter. **To our knowledge, this represents the first study globally to evaluate the chronic impact of extreme ambient on an 'ultrapure' healthy older adults population using such a decadal filter, providing the first regional evidence in Southeast Asia that integrates a quasi-longitudinal framework to isolate respiratory effects. Utilizing a Precision Public Health (PPH) framework, this study aimed to determine the translational impact** of chronic $PM_{2.5}$ exposure on **standardized lung function** (**GLI 2012 - z-scores, adjusted for South East Asian populations**) among **'apparently healthy'** older adults Indonesians, thereby providing a unique regional evidence for targeted promotive and preventive public health strategies. **Methods:** We conducted **a natural experiment with quasi-longitudinal approach. Applying a two-tiered assessment strategy, this study involved 101 non-smoking older adults adults (age 65–80 years; normal BMI). This design compared two populations with a minimum 10-year residency in areas of contrasting $PM_{2.5}$ levels: a high-exposure urban area (Kedoya) and a low-exposure rural area (Pangalengan). The decade-long residency requirement ensured that exposure preceded the outcome, thereby minimizing reverse causality. To ensure comparability across different altitudes and temperatures, spirometry was performed using internal BTPS (Body Temperature, Ambient Pressure, Saturated with water vapor) compensation. Multivariable linear regression** was used to evaluate the association between residential $PM_{2.5}$ exposure and lung function, **adjusting for key demographic and lifestyle covariates**. **Results:** Older adult participants in the high-exposure area had significantly lower FEV1_z and FVC_z values compared to those in the low-exposure area. No significant difference was observed for the FEV1/ FVC_z ratio. Multivariate regression confirmed that exposure group (urban vs. rural) was the only independent predictor of FEV1_z (β=–1.42, $p<0.001$) and FVC_z (β=–1.14, $p<0.001$), after adjusting for covariates. No violation of model assumptions was detected for these outcomes. **Conclusions: By utilizing a natural experiment design with a decade of stable exposure, this study demonstrates** that high $PM_{2.5}$ exposure is associated with significant reductions in standardized lung volumes (FEV1_z, and FVC_z) among older adults, even after adjusting for demographic factors. The finding that the FEV1/FVC_z ratio remains unaffected suggests that chronic particulate exposure primarily contributes to **restrictive-type impairment**. **The 10-year exposure stability strengthens the causal inference by ensuring temporal precedence.** This study provides **actionable translational evidence** for **robust promotive and preventive measures**, emphasizing the urgent need for stringent air quality management—including **expanding green spaces** and **integrating environmental risk assessments into geriatric care. Ultimately, these findings support a shift toward early detection through targeted respiratory screening and individualized risk assessments to protect vulnerable older adults in highly polluted megacities.**

Keywords: GLI-2012 z-scores, **natural experiment design**, older adults, $PM_{2.5}$ exposure, **Precision Public Health**, **promotive and preventive strategies**, **quasi-longitudinal approach**.

INTRODUCTION

Ambient air pollution, particularly fine particulate matter ($PM_{2.5}$), remains one of the leading environmental risk factors for morbidity and mortality worldwide [1,2,3,4,5]. $PM_{2.5}$ can penetrate deep into the distal airways, triggering inflammation, oxidative stress, and structural changes that contribute to impaired pulmonary function [1,3,6,7,8,9]. Older adults are especially vulnerable due to age-related physiological decline, higher prevalence of comorbidities, and reduced capacity to respond to environmental stressors [7,10,11]. **This heightened susceptibility underscores the need for a Precision Public Health approach, which moves beyond population-wide averages to focus on tailored promotive and preventive strategies for highly vulnerable subgroups** [12,13,14].

Despite extensive evidence linking $PM_{2.5}$ exposure with adverse respiratory outcomes, the majority of epidemiological research has focused on children or middle-aged adults [4,8]. Studies involving older adult populations—who bear a disproportionate burden of air-pollution-related disease—remain relatively scarce, particularly in low- and middle-income countries (LMICs) (2,6,10). Moreover, data from cities with extremely high ambient $PM_{2.5}$ levels are limited, restricting our understanding of how chronic exposure affects lung function in the most heavily polluted urban environments [3,6,7,8,9]. This lack of data is critical, **as it hinders the development of precision-based preventive interventions tailored to the older adults, whose physiological response to extreme pollution may differ significantly from documented patterns in younger cohorts** [10].

Jakarta has repeatedly ranked among the most polluted major cities globally, with annual $PM_{2.5}$ concentrations far exceeding WHO guidelines [2,15]. However, substantial variation in $PM_{2.5}$ levels exists across districts, driven primarily by high-volume traffic emissions and localized urban construction projects [15, 16]. This provides a unique opportunity to employ a **natural experiment framework** [17,18,19,20]. **In the context of Precision Public Health, utilizing such high-contrast environmental gradients allows for a more granular understanding of how localized exposure impacts specific demographics. Such evidence is foundational for designing targeted health promotion programs and providing the causal rigor needed for effective policy-making.** Unlike standard cross-sectional studies that often lack the temporal depth to establish causal links, this study utilizes the extreme pollution contrast between two distinct regions as a **quasi-gold standard** for environmental observation [17,18,19,20]. By enforcing a strict **10-year minimum residency requirement**, we introduce a **quasi-longitudinal perspective** [21,22] that minimizes common pitfalls such as exposure misclassification and reverse causality, effectively **bridging the ethical and methodological gap** between observational surveys and randomized trials.

To our knowledge, **this is the first study globally to apply a Precision Public Health lens by evaluating the chronic impact of extreme ambient $PM_{2.5}$ on an 'ultrapure' healthy older adult population using a 10-year stable residency filter within a natural experiment framework.** Furthermore, it represents **a pioneering application** of this quasi-longitudinal approach globally, providing unique evidence from one of the world's most polluted megacities to **inform evidence-based preventive measures**.

To address this evidence gap, we conducted a **natural experiment framework** to compare lung function, expressed as Global Lung Initiative (GLI) z-scores [23,24], between older adult residents of two areas with distinctly different annual $PM_{2.5}$ levels. Our methodology leverages this this **'as-if random' assignment** to ensure that the measured lung function **reflects long-term, cumulative impacts** rather than acute environmental shifts, thereby establishing the necessary **temporal precedence for causal inference**. Furthermore, the use of standardized spirometric z-scores (GLI-2012) specifically adjusted for South East Asian ethnicity allows for a pioneering assessment of the aging lung in this region. **This methodological precision is essential for Precision Public Health, ensuring that clinical assessments are ethnically and age-appropriately accurate, thereby avoiding the misdiagnosis common in generalized respiratory models and improving the efficacy of primary prevention.**

The primary research questions were: (1) whether long-term exposure drives lower and z-scores among older adults; and (2) whether exposure leads to significant differences in z-scores. We hypothesized that older adult individuals living in the higher-exposure area would exhibit lower lung volumes (FEV_1_z and FVC_z), reflecting a subclinical restrictive-like decline, with less pronounced differences in the FEV_1/ FVC ratio. **These findings are expected to provide the granular evidence necessary for developing robust promotive and preventive public health strategies for aging urban populations.**

METHODS

Study Design

We employed **a natural experiment using a quasi-longitudinal approach** to compare lung function among older adults residing in two areas with markedly different long-term ambient exposure levels. **This design—often regarded as a quasi-gold standard for evaluating environmental exposures—was specifically chosen to bridge the ethical gap where a Randomized Controlled Trial (RCT) is impossible** [25,26,27]. The substantial between-area variation in levels serves as **an exogenous proxy for random assignment,** allowing for a **population-level comparison that minimizes selection bias. By utilizing these extreme environmental gradients, we simulated a 'quasi-experimental' condition that approaches the causal rigor of an RCT while maintaining real-world translational relevance. This design aligns with the Precision Public Health framework by moving beyond population-wide averages to evaluate how specific, localized environmental stressors impact a highly vulnerable sub-population.**

To strengthen the quasi-longitudinal perspective of this design, we enforced **a strict 10-year minimum residency requirement** for all participants. **This residency threshold ensures that the measured lung function reflects the cumulative, long-term impact of chronic exposure rather than acute environmental shifts.** By establishing **the necessary temporal precedence,** this design addresses **a key requirement for causal inference and significantly reduces the risk of reverse causality** often found in standard cross-sectional studies.

To our knowledge, this is the first study globally to utilize such a decadal exposure filter within a natural experiment to assess an 'ultrapure' older adults cohort in a high-pollution megacity.

The study was conducted in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines [28,29] to ensure transparent reporting. By comparing two geographically distinct populations that are socio-demographically similar but environmentally contrasted, we effectively utilized this **"natural contrast"** to assess the chronic impact of particulate matter on the aging lung while **minimizing confounding** through **strict eligibility criteria** and **frequency matching.**

Study Setting and Site Selection

The study utilized a two-tiered exposure assessment strategy—a two-stage hybrid approach—to characterize exposure and select research sites by combining macro-level secondary data with micro-level direct environmental sampling. This methodology was employed to ensure a high-contrast exposure gradient while validating area-specific concentrations through ground-truthing [30]. In the first stage (Macro-level Mapping), preliminary mapping was conducted using secondary data from government air quality monitoring stations across the Jakarta and Bandung metropolitan areas to identify regions with the highest and lowest historical levels.

This was followed by a second stage of primary validation (Micro-level Direct Measurement) to capture real-time, area-specific concentrations and minimize the risk of ecological fallacy. Three specific districts within the candidate regions of Jakarta and Bandung were selected for direct on-site monitoring to validate actual ambient conditions within residential neighborhoods. This granular validation is a cornerstone of the Precision Public Health framework, ensuring that the exposure contrast is not merely assumed from distant monitoring stations but verified at the residential level, thereby reducing exposure misclassification. Based on the synthesis of these multi-level data points, Kedoya (Jakarta) was confirmed as the high-exposure location and Pangalengan (Bandung Regency) as the lower-exposure location. Participants were subsequently assigned to exposure categories using an area-level proxy that reflected the validated chronic ambient conditions of their primary residence.

Sample Size Determination

A minimum sample size of 34 participants per group was estimated using a **two-sample comparison of means**, assuming a significance level of α=0.01 and 95% power [31,32,33,34]. This calculation employed the standard formula for comparing two independent means:

$$n = \frac{(Z_{\alpha/2} + Z_{\beta})^2 \cdot 2\sigma^2}{(\mu_1 - \mu_2)^2}$$

Where:

- n: Minimum sample size required per group.
- $Z_{\alpha/2}$: The Z-score corresponding to the two-tailed significance level ($\alpha=0.01$, $Z_{\alpha/2}\approx2.58$).
- Z_{β}: The Z-score corresponding to the desired power ($1-\beta=0.95$, $Z_{\beta}\approx1.64$).
- μ1−μ2: The expected minimum mean difference between the high- and low-exposure groups.
- σ: The population standard deviation of the outcome variable (FEV1_z).

The power calculation was based on an expected mean difference in FEV1_z-scores (μ1−μ2) of 0.8 units (assuming a standard deviation (σ) of 1.0), derived from previous similar epidemiological studies on air pollution effects in older adult populations. To account for potential exclusions, invalid spirometry, and data loss, the recruitment target was increased to at least 60 participants per group [31,34].

Participants Recruitment and Eligibility

Data collection was conducted between May and June 2025 across two districts representing high (Kedoya) and low (Pangalengan) exposure gradients. To enhance internal validity and minimize variability in major confounding factors, participants were selected through a multi-layered screening process designed to ensure that observed differences in lung function were primarily attributable to ambient exposure rather than individual health histories or lifestyle choices. This 'ultrapure' cohort selection serves a translational purpose; by isolating the impact of exposure from other major confounders, the findings provide clear, actionable evidence for clinical guidelines and public health protection for the older adult population.

Eligibility was determined based on strict inclusion and exclusion criteria. Participants were **included** if they were aged between 65 and 80 years and had maintained permanent residence at their current address for at least ten continuous years. This decadal residency criterion is crucial to ensure that the measured lung function reflects the long-term, cumulative impact of chronic exposure rather than acute environmental changes, effectively establishing a retrospective temporal order between exposure and outcome. Additionally, candidates were required to demonstrate the willingness and physical ability to undergo standardized spirometry and structured interviews, and must fall within the normal Body Mass Index (BMI) range (18.5–22.9 kg/m^2) as defined by the WHO classification for Asian populations [35,36]. This BMI restriction was applied to exclude the potential restrictive effects of obesity on lung expansion [37,38].

To further minimize confounding bias, several **exclusion criteria** were rigorously applied. Individuals were excluded if they were current or former active smokers or had significant daily exposure to passive smoking. Potential participants with a known history of chronic respiratory diseases—including COPD, pulmonary fibrosis, uncontrolled asthma, or history of pulmonary tuberculosis—were also excluded, as were those with recent acute respiratory tract infections within the preceding four weeks. Furthermore, the study excluded individuals with severe cardiovascular or systemic conditions, lung cancer, or neuromuscular and cognitive impairments that could interfere with spirometry validity or the ability to follow instructions. Finally, to isolate ambient as the primary factor, individuals with significant occupational exposure to industrial dust, biomass smoke, or chemical irritants, as well as those with communication barriers such as illiteracy, were not included in the final cohort.

Sampling and Final Sample

The recruitment and selection process followed a systematic multi-stage purposive sampling approach to ensure a high-quality, comparable study population (See Figure 1 – STROBE Flowchart). In the first and second stages, purposive selection was used to identify regions and specific sites (Kedoya and Pangalengan) with extreme contrast. In the third stage, a sampling frame of 245 potential candidates was established through registries at community health posts (Posbindu). These candidates underwent preliminary pre-screening to verify basic eligibility based on age (65–80 years), never-smoking status, and a 10-year stable residency requirement.

From this registry, a simple random sampling procedure was employed to invite 60 candidates from each site (total n=120) for formal clinical assessment to minimize selection bias. A total of 123 individuals attended the clinical phase (68 from Kedoya and 55 from Pangalengan). These candidates underwent a rigorous one-day comprehensive clinical screening, comprising structured interviews, physical examinations, and Electrocardiography (ECG) to rule out cardiovascular abnormalities. To enhance comparability and neutralize potential confounders—such as age, gender, education level, and occupation—a frequency matching procedure was applied. After strictly adhering to the ATS/ERS 2019 quality standards for spirometry [39], the final analytical sample consisted of 101 participants (54 from the higher-exposure area and 47 from the lower-exposure area).

Research Variables and Operational Definitions

This study involved several key variables classified into independent, dependent, and covariate variables. The independent variable was the level of chronic fine particulate matter () exposure, represented by the participants' residential location, with the Kedoya area categorized as high exposure and Pangalengan as low exposure. A primary focus of this study

was the assessment of lung function as a continuous physiological measure rather than a binary clinical diagnosis. This approach increases statistical power and allows for the detection of subclinical declines in respiratory health, representing a key feature of the Precision Public Health framework by identifying 'at-risk' individuals before overt clinical disease manifests.

The primary outcomes were lung function indices expressed as and z-scores, calculated using the Global Lung Initiative (GLI) 2012 Southeast Asian reference equations to account for age, sex, and height. Analyzing these as continuous variables enables the detection of subtle, dose-dependent shifts in lung function associated with chronic exposure. Secondary outcomes included the z-score and the prevalence of lung function impairment. Clinical obstruction was defined using an age-appropriate threshold for older adults, specifically an z-score below −1.64 (the Lower Limit of Normal), while participants with a z-score ≥−1.64 were classified as having a normal ventilatory pattern.

Covariate variables were collected for descriptive analysis, frequency matching, and statistical adjustment. These included age (years), gender (male or female), and height (cm). Body Mass Index (BMI) was calculated as weight in kilograms divided by the square of height in meters (). In accordance with the inclusion criteria, all participants were within the WHO-defined normal range for Asian populations. BMI served both for frequency matching and as a covariate in multivariable models, with an independent sample t-test confirming no statistically significant difference in mean BMI between the two exposure groups to ensure baseline comparability of nutritional status. Socioeconomic status (SES) was captured through education level—categorized into low (no schooling/primary), middle (junior/senior high), and higher education (diploma/degree)—and occupation, which was grouped ordinally into three levels: (1) unemployed, laborer, farmer, or small trader; (2) employee; and (3) professional.

Research Instruments

Data collection was facilitated through a suite of validated instruments designed to capture demographic, socioeconomic, and physiological variables. A pre-tested structured questionnaire was utilized to gather respondent identity, socioeconomic status (including education and occupation), and a detailed 10-year residency history. To ensure the 'ultrapure' nature of the cohort, the questionnaire also screened for histories of chronic or acute lung diseases and environmental confounding factors, such as passive smoking and biomass exposure. All measurements were recorded on a standardized observation sheet, which included height measurements taken with a calibrated stadiometer to the nearest centimeter. Ethical adherence was documented through signed informed consent forms, which were obtained after participants received comprehensive information regarding the study's objectives and procedures.

Pulmonary function was assessed using a portable digital spirometer to measure Forced Expiratory Volume in 1 second (FEV_1), Forced Vital Capacity (FVC), and the FEV_1/ FVC ratio. The device maintained a volume accuracy of 3% and a flow range of 0–16 L/s, with calibration performed before each session to ensure data integrity. All measurements were conducted by trained personnel in strict accordance with the American Thoracic Society/European Respiratory Society (ATS/ERS) standards. Participants received standardized instructions and demonstrations prior to the examination, with maneuvers repeated until at least two consistent, high-quality results were obtained. To further validate site conditions and technical reporting, visual documentation was utilized for location-specific field notes and activity verification, while strictly maintaining participant anonymity.

Data Collection Methods

Data collection was conducted directly at the two research locations by a trained survey team comprising enumerators, medical personnel, and field coordinators. The fieldwork utilized standardized procedures and instruments, beginning with a community-based recruitment process. After passing initial pre-screening and prior to any clinical procedures, participants received a comprehensive explanation of the study and provided written informed consent. Face-to-face interviews were then conducted using a piloted structured questionnaire to collect demographic data, socioeconomic factors, residency history, and detailed medical histories related to the exclusion criteria. To minimize information and observer bias, all interviews were conducted by trained enumerators who were blinded to the participants' exposure status.

Participants subsequently underwent standardized physical and supporting examinations. Anthropometric measurements, including body weight and height (measured using a portable stadiometer), were taken to confirm that all participants met the normal BMI inclusion criteria (18.5–22.9 kg/m^2). This was followed by a cardiorespiratory assessment—encompassing blood pressure, heart rate, respiratory rate, oxygen saturation, and lung/heart auscultation—and an Electrocardiogram (ECG) to exclude severe cardiovascular conditions. All clinical examinations were performed by medical personnel who were blinded to the geographic exposure classification of the participants.

Pulmonary function was measured using a portable digital spirometer in strict accordance with the American Thoracic Society (ATS) and European Respiratory Society (ERS) standards [38]. Participants performed maneuvers in a seated position, and measurements were repeated until at least dua consistent best results were obtained, with a difference in and between maneuvers not exceeding 150 mL. To ensure data validity across the geographically distinct study sites of Kedoya and Pangalengan, the following protocols were implemented. First, to account for significant differences in temperature and atmospheric pressure between the coastal Jakarta area and the highland Bandung region, the spirometer was equipped with an internal BTPS (Body Temperature, Ambient Pressure, Saturated with water vapor) sensor. This sensor automatically calibrated and adjusted measured lung volumes based on ambient conditions at each site, ensuring that the results reflected true physiological capacity. This environmental compensation ensured the precision of the biological signal across disparate geographic altitudes. Second, raw lung function values were converted into z-scores using the Global Lung Initiative (GLI) 2012 South East Asian-

adjusted reference equations to account for ethnic-specific lung morphology. This approach minimized bias related to age, height, and ethnicity, while all spirometry technicians remained blinded to participants' exposure status to ensure objective outcome measurement.

Air Pollution Exposure Data

Air pollution exposure data ($PM_{2.5}$ levels) were obtained from long-term environmental monitoring data at the participants' residential areas, which served as the basis for categorizing participants into the high and low exposure groups.

Data Recording and Quality Control

All data were recorded on standardized worksheets. Data quality control involved review by a field supervisor, reconfirmation of incomplete or questionable data, and double data entry to minimize input errors and ensure accuracy.

Outcome Measures

The primary outcomes of this study were standardized lung function indices, which facilitate an accurate comparison between individuals across different ages, heights, and genders. We focused on three key parameters to assess pulmonary health: Forced Expiratory Volume in 1 second (FEV_1), Forced Vital Capacity (FVC), and the FEV_1/ FVC ratio, the latter of which is used to identify obstructive ventilatory defects. To minimize the bias inherent in using absolute values or percentage of predicted values—which can vary significantly in older adult populations—all raw measurements were **converted into z-scores** using the Global Lung Function Initiative (GLI-2012) reference equations.

A z-score indicates how many standard deviations an individual's measurement deviates from the mean predicted value of a healthy population. This standardization ensures that differences in lung function between the high and low exposure groups are not confounded by individual anthropometric characteristics, including age, height, gender, and ethnicity. For the clinical categorization of impairment, participants were classified as having a ventilatory defect if their FEV_1_z, FVC_z, or FEV_1/ FVC_z-score fell below the Lower Limit of Normal (LLN). Following international diagnostic standards, the LLN was defined as a **z-score of less than −1.645**, which corresponds to the 5th percentile of the healthy reference population.

Data Quality and Handling of Missing Data

To ensure high data integrity, a complete case analysis was adopted. Given the direct supervision during data collection, missingness was minimal. Any participants with invalid spirometry or incomplete responses were replaced in real-time by new recruits from the same strata to maintain the required statistical power.

Statistical Analysis

Participant characteristics were summarized using descriptive statistics. Initially, the effectiveness of the frequency matching procedure was verified by comparing baseline characteristics between the high and lower-exposure groups using Independent Samples t-tests (or Mann-Whitney U tests) for continuous variables and Chi-square tests for categorical variables.

Data normality was assessed using the **Shapiro-Wilk test,** as it is more sensitive and robust for the current sample size per group (n<100), supplemented by visual inspection of Q-Q plots. Homogeneity of variances was evaluated using **Levene's test**. Group differences between exposure areas were assessed using **Independent Samples t-tests** for variables meeting parametric assumptions or nonparametric alternatives (**Mann-Whitney U**) for variables that violated normality or homogeneity assumptions.

Multivariable linear regression models were fitted to estimate the association between $PM_{2.5}$ exposure category and each lung function z-score (FEV_1_z, FVC_z, and FEV_1/FVC_z-score). Models were adjusted for age, sex, body mass index, socioeconomic indicators. Results are reported as adjusted mean differences (Unstandardized B coefficients) with 95% confidence intervals. Model assumptions were strictly verified using **the Kolmogorov–Smirnov test was used to confirm the normality of unstandardized residuals (with a significance threshold of p>0.01), multicollinearity** was assessed using the **Variance Inflation Factor (VIF < 5.0)**, and influential outliers were screened using **Cook's distance (threshold < 1.0)**, and **Mahalanobis distance with the latter evaluated against the $\chi 2$ critical value for the corresponding degrees of freedom (p<0.001).** Statistical analyses were conducted using SPSS version 26. All hypothesis tests were evaluated using a two-tailed significance level of **α=0.01** and **power=95%, providing the high-precision evidence necessary for translational health applications.**

Ethical considerations

The study was conducted in accordance with the **Declaration of Helsinki** and **approved by the Ethical Review Committee of the Faculty of Medicine, Universitas Trisakti** under ethical permission number 007/KER/FK/04/2025. Prior to participation, all individuals provided **written informed consent**. To ensure genuine autonomy among the older adults participants, the consent process included a comprehensive verbal explanation of the study's objectives and the non-invasive nature of the procedures.
Researchers ensured that all technical terms were explained in **lay language**, and for those with age-related visual difficulties, the form was read aloud to guarantee full comprehension before signing. Participation was strictly voluntary, with the right to withdraw at any time without consequence. Each consent form was signed by the participant and **witnessed by an impartial third party** present during the process. Individuals who were illiterate or could not speak Indonesian were excluded to ensure the integrity of the informed consent process. As the study focused exclusively on the older adults, no minors were involved.
To safeguard privacy, all data were **double-anonymized** using unique alphanumeric codes; no identifying information was stored in the final analytic dataset. All clinical examinations were conducted in private settings to maintain the dignity and comfort of the participants.

RESULTS

A. Participant Flow and Selection. The flow of participants throughout the study, detailing the recruitment process, application of inclusion/exclusion criteria, and the final analytic sample size, is illustrated in Figure 1. A total of 123 older adults residents were initially screened. After applying eligibility criteria (e.g., age 65–80 years, minimum 10-years residency, no history of smoking) and excluding 22 participants, the final analytic sample consisted of 101 older adults adults. Specifically, **47 participants** from the low-exposure Pangalengan group and **54 participants** from the high-exposure Kedoya group were included in the final analysis. The Pangalengan group consisted of **37 older adults women and 10 older adults men**, while the Kedoya group comprised **47 older adults women and 7 older adults men.**

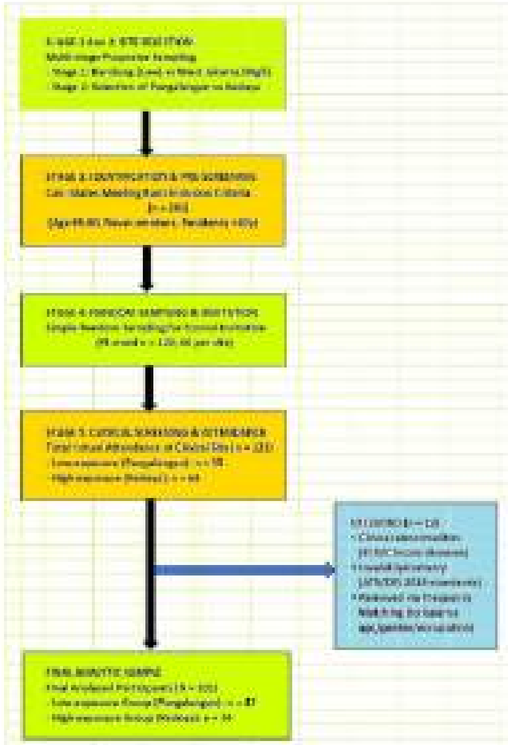

Figure 1. STROBE Flowchart of the multi-stage participant selection process. The diagram illustrates the recruitment stages, including site selection (Stages 1–2), identification and pre-screening (Stage 3), random sampling for invitation (Stage 4), and clinical validation. The final analytical sample was established after frequency matching and rigorous filtration to ensure a healthy, comparable groups.

B. Study Setting and Exposure Assessment

$PM_{2.5}$ concentration measurements were conducted at six preliminary locations: three in the Bandung area (characterized by generally low $PM_{2.5}$ levels) and three in Jakarta (characterized by generally high $PM_{2.5}$ levels). This initial screening was performed to identify the most suitable study locations for participant recruitment. Based on the collected data, one location in the Bandung area exhibiting the lowest $PM_{2.5}$ concentration and one location in Jakarta with the highest $PM_{2.5}$ concentration were subsequently selected for the

study. The measurement results for AQI (Air Quality Index), , and from all six preliminary locations are presented in Table 1.

Table 1. AQI (Air Quality Index), PM2.5 and PM10 Concentrations in Preliminary Measurement Areas.

Area	Location	AQI	PM2.5 (µg/m3)	PM10 (µg/m3)
Bandung	Pangalengan	43	10	17
	Leuwi Panjang	179	36	87
	Padalarang	191	40	94
Jakarta	Kedoya	219	57	156
	Cilandak barat	216	54	151
	Mangga Dua	209	45	127

C. Participant Characteristics

Baseline demographic and clinical characteristics are detailed in **Table 2.** The two exposure groups were generally comparable across most variables, confirming the **effectiveness of the frequency matching procedure** outlined in the Methods section. Mean age in the low-exposure group (Group 1) was 71.32 years vs 71.52 years in the high exposure group (Group 2). The difference in mean age (Mean Differences=−0.199 years) was not statistically significant ($t=-0.317$, $p=0.747$). Homogeneity of variance for age was also confirmed by Levene's test ($F=5.075$, $p=0.026$, consistent with $\alpha=0.01$ as the criterion).

Similarly, the distribution of gender was comparable, with the majority being female in both groups (Pangalengan: 78.72% female vs. Kedoya: 87.04% female, $\chi 2$ test $p = 0.265$). The lack of significance difference in mean age and gender distribution demonstrated that the groups were well-balanced for these important covariates. No data were missing for lung function variables or covariates.

The anthropometric profile, specifically Body Mass Index (BMI), also showed no significant difference between the two groups. The mean BMI in the low-exposure group was **20.74 kg/m^2** compared to **20.80 kg/m^2** in the high-exposure group (**Mean Difference = -0.066 kg/m^2**). This difference was not statistically significant (**$t = -0.441$, $p = 0.661$**). Homogeneity of variance for BMI was confirmed by Levene's test (**$F = 1.197$, $p = 0.277$**), further demonstrating that the groups were well-balanced regarding nutritional status.

Table 2. Demographic and Anthropometric Characteristics of Study Participants by Data Collection Location.

Characteristics	Pangalengan	Kedoya	Total
Gender:			
- Male	10 (21.28%)	7 (12.96%)	17 (16.83%)
- Female	37 (78.72%)	47 (87.04%)	84 (83.17%)
Number of Participants	47 (100%)	54 (100%)	101 (100%)
Education:			
- Low: Not attending school, Elementary school	37 (72.34%)	38 (70.37%)	75 (74.26%)
- Middle: Junior and Senior High School	9 (19.14%)	14 (25.93%)	23 (22.77%)
- High: diploma, bachelor	1 (2.13%)	2 (3.70%)	3 (2.97%)
Occupation:			
- unemployed, laborers, farmers, small traders	47 (100%)	54 (100%)	101 (100%)
- employee	0 (0%)	0 (0%)	0 (0%)
- professional	0 (0%)	0 (0%)	0 (0%)
Age	Mean=71.32, SD=2.59	Mean=71.52, SD=3.57	
Height	Mean=147.53, SD=7.21	Mean=151.30, SD=6.04	
Normal Body Mass Index (18.5-22.9 kg/m2)	Mean=20,74, SD=0.80	Mean=20.80, SD=0.70	
Ethnicity	Southeast Asia	Southeast Asia	

To compare the characteristics of the study subjects between the Pangalengan group (Group 1) and the Kedoya group (Group 2), a series of statistical tests were conducted, including normality of distribution tests, homogeneity of variances tests, and mean or median comparison tests. A comprehensive summary of these test results is presented in **Table 3.**

Table 3. Summary of Statistical Test Results for Inter-Group Characteristic Comparisons.

Variable Compared	Normality Test Group 1 / Group 2)	Variance Homogeneity (Levene's Sig.)	Comparison Test Used	Test p-value	Conclusion
Test of Difference in Proportions of Groups 1&2	N/A (Categorical)	N/A	Chi-Square Goodness of Fit Test	0.486	No significance different
Test of Difference in Gender Proportion* Group 1&2	N/A (Categorical)	N/A	Chi-Square of Independence Test	0.265	No significance different
Test of Difference in Education Proportion* Group 1&2	N/A (Categorical)	N/A	Chi-Square (Monte-Carlo exact)	0.663	No significance different
Age: Group 1 Group 2	0.146 (Normal Distribution) 0.102 (Normal Distribution)	0.026 (Homogeneous)	Welch / Brown-Forsythe	0.747	No significance different
Height: Group 1 Group 2	0.175 (Normal Distribution) 0.162 (Normal Distribution)	0.337 (Homogeneous)	Welch / Brown-Forsythe	0.006 (Welch/Brown-Forsythe)	Significance different
Body Mass Index: Group 1 Group 2	0.536 (Normal Distribution) 0.111 (Normal Distribution)	0.277 (Homogenous)	Independent Sample t-test	0.661	No significance different

Note: Group 1: Pangalengan; Group 2: Kedoya; N/A: Not Applicable.

D. Lung Function Differences Between Exposure Groups

Participants residing in the higher exposure area exhibited lower mean FEV1_z-scores and FVC_z-scores compared with those living in the lower-exposure area. In contrast, the FEV1/FVC z-score remained comparable between the two groups.

1. Comparison of Z-Scores (Adjusted Parameters)

For the z-scores (FEV1_z and FVC_z), which adjust for age, gender, and height, the analysis revealed the following:

FEV1_z (Non-parametric Test): Due to the violation of the normality assumption in group 1 ($p=0.001$) and unequal variances (Levene's $p<0.001$), the Mann-Whitney U test was performed. The test revealed **a highly statistically significant difference** ($p<0.001$). The lower-exposure group showed a higher distribution (Mean Rank = 64.63) compared to the higher-exposure group (Mean Rank = 39.14), with a Mean Rank difference of +25.49.

FVC_z (Parametric Test): As the $\alpha=0.01$ significance level, FVC_z satisfied the assumption for parametric analysis. Both groups followed a normal distribution (Shapiro-Wilk $p=0.054$ and $p=0.989$) and demonstrated homogeneity of variances (Levene's $p=0.051$). Consequently, an **Independent Samples t-test** was performed. The test indicated a **highly statistically significant difference** between the two exposure groups ($p<0.001$).

- **The Mean Difference ($\mu1-\mu2$)** was calculated as +1.2111 **z-score units** (Mean 1 = −1.2409; Mean 2 = −2.4520), corresponding to a **large effect size (Cohen's d=1.21**). This indicated that the average **FVC_z score** in the lower-exposure group was **1.21 Standard Deviations (SDs) higher** than the higher-exposure group.

FEV1/ FVC_z Ratio: Consistent with the primary findings, the Mann-Whitney U test for the FEV1/ FVC_z ratio showed **no statistically significant difference** between the two groups ($p=0.464$). Both groups maintained average values (+1.96 and +1.57, respectively) well above the clinical threshold for obstruction (Lower Limit of Normal = −1.64). This result is consistent with the study's recruitment process, which excluded individuals with known respiratory diseases or overt symptoms of breathlessness, thereby ensuring a study population of 'apparently healthy' older adults. Consequently, the proportional relationship between and remained preserved, confirming an absence of airway obstruction even in the higher-exposure group. **Notably, both the lower-exposure group (+1.96) and the higher-exposure group (+1.57) maintained mean values well above the clinical threshold for obstruction (LLN=−1.64). This result aligns with the study's recruitment process, which excluded individuals with known respiratory diseases or overt symptoms of breathlessness to ensure a population of 'apparently healthy' older adults. Consequently, while absolute volumes (FEV1_z and FVCz) were significantly reduced, the proportional relationship between them remained preserved, confirming an absence of airway obstruction even in the higher-exposure group.**

2. Consistency in Actual Parameters

This pattern was consistently mirrored in the analysis of actual lung function parameters (FEV1_actual and FVC_actual):

- The mean FEV1_actual was significantly lower in the high-exposure group (Independent -test, $p<0.001$).
- The median FVC_actual also showed a statistically significant difference (Mann-Whitney U test, $p=0.002$).
- Correspondingly, no significant difference was detected in the median FEV1/ FVC_actual ($p=0.687$).

These findings strongly suggest that differences in $PM_{2.5}$ exposure were primarily associated with reductions in absolute **lung volumes** (FEV1_z and FVC_z), rather than an alteration in the underlying **airway resistance pattern** (as indicated by the non-significant FEV1/ FVC_z ratio).

The complete comparison results for both actual and z-scores lung function parameters are detailed in **Table 4.**

Table 4. Summary of Statistical Tests for FEV_1, FVC, and FEV_1/FVC Variables.

Variable	Group	Normality Test (Shapiro-Wilk Sig.)	Homogeneity of Variance (Levene's Sig.)	Tests Performed	Sig. Test Results	Conclusion (Differences Between Groups)
FEV1_actual	1	0.019 (Normal)	0.672 (Homogeneous)	Independent Samples t-test	<0.001	Significant Difference
	2	0.058 (Normal)				
FVC_actual	1	0.008 (Non Normal)	0.634 (Homogeneous)	Mann-Whitney U	0.002	Significant Difference
	2	0.520 (Normal)				
FEV1FVC_actual	1	0.000 (Non Normal)	0.058 (Homogeneous)	Mann-Whitney U	0.687	No Significant Difference
	2	0.000 (Non Normal)				
FEV1_z	1	0.001 (Non Normal)	0.000 (Not Homogeneous)	Mann-Whitney U	<0.001	Significant Difference
	2	0.369 (Normal)				
FVC_z	1	0.054 (Normal)	0.051 (Homogeneous)	Independent Samples t-test	<0.001	Significant Difference
	2	0.989 (Normal)				
FEV1FVC_z	1	0.000 (Non Normal)	0.017 (Not Homogeneous)	Mann-Whitney U	0.464	No Significant Difference
	2	0.000 (Non Normal)				

Abbreviations: FEV_1 – Forced Expiratory Volume in 1 second; FVC – Forced Vital Capacity; FEV_1/FVC – Ratio of FEV_1 to FVC; FEV_1_actual – Measured absolute value of FEV_1 (in liters); FVC_actual – Measured absolute value of FVC (in liters);FEV_1/FVC_actual – Measured absolute ratio of FEV_1 to FVC; FEV_1_z – Standardized Z-score of FEV_1 (adjusted for age, gender, and height); FVC_z – Standardized Z-score of FVC (adjusted for age, sex, and height); FEV_1/FVC_z – Standardized Z-score of the FEV_1/FVC ratio; Sig. – Significance (p-value); Levene's Sig. – p-value from Levene's test for homogeneity of variances.

E. Correlation Analysis between Covariates and Lung Function

To explore potential confounders and inform the subsequent multivariable model, bivariate correlations were examined between selected participant characteristics (covariates) and

lung function z-scores. The complete correlation matrix, including the results of both Pearson (r) and Spearman (ρ) tests, is summarized in Table 5.

The key finding confirmed the inverse association observed in the descriptive analysis: Ambient $PM_{2.5}$ exposure demonstrated a significant and moderate negative correlation with both FEV1_z (Pearson r=−0.469, p<0.001) and FVC_z (Pearson r=-0.462, p<0.001). This suggests that higher levels are associated with lower lung volumes relative to reference values. Consistent with the group comparison results, $PM_{2.5}$ exposure was not statistically significantly associated with the FEV_1/FVC_z ratio (Pearson r=−0.136, p=0.176).

Regarding the covariates, Age, Gender, Education, and Body Mass Index (BMI) showed no statistically significant correlations with any of the lung function outcomes when evaluated at the prespecified significance level of p<0.01. However, Height showed a significant, weak negative correlation with FVC_z (Pearson r=−0.273, p=0.006), suggesting a potential weak confounding effect that should be controlled for in the regression analysis.

Table 5. Pearson Correlation and Spearman's rho Matrix between $PM_{2.5}$ Exposure, Covariates and Lung Function Variables in the Older adults.

Variables	Pearson r Correlation Coeff (p)	Spearman's ρ Correlation Coeff (p)	Conclusion
PM2.5 vs FEV1_z	-0.469 (p<0.001)	-0.486 (p<0.001)	Significant and moderate negative correlation
PM2.5 vs FVC_z	-0.462 (p<0.001)	-0.457 (p<0.001)	Significant and moderate negative correlation
PM2.5 vs FEV1/FVC_z	-0.136 (p=0.176)	-0.072 (p=0.467)	Not statistically significant
Gender vs FEV1_z	0.078 (p=0.438)	0.058 (p=0.561)	Not statistically significant
Gender vs FVC_z	0.099 (p=0.324)	0.118 (p=0.240)	Not statistically significant
Gender vs FEV1/FVC_z	0.039 (p=0.698)	0.031 (p=0.759)	Not statistically significant
Age vs FEV1_z	-0.111 (p=0.268)	-0.136 (p=0.175)	Not statistically significant
Age vs FVC_z	-0.119 (p=0.236)	-0.122 (p=0.223)	Not statistically significant
Age vs FEV1/FVC_z	-0.085 (p=0.397)	0.138 (p=0.168)	Not statistically significant
Height vs FEV1_z	-0.238 (p=0.016)	-0.154 (p=0.118)	Not statistically significant
Height vs FVC_z	-0.273 (p=0.006)	-0.183 (p=0.066)	Significant and weak negative correlation
Height vs FEV1/FVC_z	0.166 (p=0.097)	0.062 (p=0.537)	Not statistically significant
Education vs FEV1_z	0.086 (p=0.393)	0.012 (p=0.906)	Not statistically significant
Education vs FVC_z	0.046 (p=0.648)	0.093 (p=0.345)	Not statistically significant
Education vs FEV1/FVC_z	0.204 (p=0.040)	0.196 (p=0.049)	Not statistically significant
BMI vs FEV1_z	0.154 (p=0.122)	0.146 (p=0.145)	Not statistically significant
BMI vs FVC_z	0.099 (p=0.327)	0.070 (p=0.486)	Not statistically significant
BMI vs FEV1/FVC_z	0.120 (p=0.229)	0.159 (p=0.113)	Not statistically significant

Note: Significance evaluated at $p < 0.01$ (two-tailed); $p \geq 0.01$ was interpreted as not statistically significant (NS). Conclusions were based on the appropriate correlation test according to data distribution: Spearman's rho was applied when at least one variable was non-normally distributed, and Pearson's correlation was applied when both variables were normally distributed. Magnitude guidelines (absolute coefficient): **weak** = 0.10–0.29; **moderate** = 0.30–0.49; **strong** ≥ 0.50. The sign indicates direction (negative/positive). See Table 4 for variable abbreviations.

F. Multivariable Linier Regression

Multivariable linear regression was employed to determine the independent association between exposure (group status) and lung function Z-scores. The models were **adjusted for potential confounders**, including age, gender, education, height, and BMI. The results of the three adjusted models are summarized **in Table 6**.

Model for FEV_1_z

The overall model for was **statistically significant** ($F(6.94)=7.189$, $p<0.001$), explaining approximately **31.5%** of the variance in FEV_1_z ($R^2=0.315$). In this adjusted model, **residence in the high-exposure area emerged as the only significant driver** of lower FEV_1_z (Unstandardized Coefficient $B=-1.434$, $p<0.001$). This indicates that, after controlling for all listed covariates, participants in the high $PM_{2.5}$ area had an FEV_1_z score that was 1.434 units lower than those in the low $PM_{2.5}$ area. While BMI showed a positive association ($B=0.443$, $p=0.015$), it did not meet the stringent significance threshold of 0.01. The model's validity was confirmed by a maximum Cook's distance of 0.149 and VIF values below 1.6, indicating no influential outliers or multicollinearity issues.

Model for FVC_z

Similarly, the model for FVC_z was also **statistically significant** ($F(6,94)=5.475$, $p<0.001$), accounting for **25.9%** of the variance ($R^2=0.259$). The $PM_{2.5}$ exposure group was the **sole significant predictor** (Unstandardized Coefficient $B = -1.145$, $p<0.001$), demonstrating that the impact of higher exposure on reduced lung volume remains robust after adjustment.

Model for FEV_1/ FVC_z

In contrast, the model for FEV_1/ FVC_z was **not statistically significant** ($F(6,94)=1.943$, $p=0.082$), accounting for only 11.0% of the variance ($R^2=0.110$). Consistent with the unadjusted results, **no predictor variable**, including $PM_{2.5}$ exposure ($B=-0.560$, $p=0.071$), showed a statistically significant association with the FEV_1/FVC_z ratio after adjustment.

Overall, these findings indicate that long-term exposure to elevated $PM_{2.5}$ levels is significantly associated with reduced lung volumes (FEV_1_z and FVC_z) but not with evidence of obstructive impairment (indicated by the FEV_1/FVC_z ratio) in this older adults population.

Table 6. Summary of Multivariable Linear Regression Analysis

Variables	R^2 (Adj. R^2)	F (df)	p-value Model	Prediktor Signifikan ($p < 0.01$)	VIF Maks	Tolerance Min	Std. Residual Range	Cook's D Max	Mahalanobis D Max	Remarks
FEV_1_z	0.315 (0.271)	$F(6, 94) = 7.189$	< 0.001	Group ($PM_{2.5}$), $p < 0.001$	1.562	0.64	-2.058 to +2.676	0.149	20.338	**Model significant; assumptions met; no outliers or multicollinearity detected.**
FVC_z	0.259 (0.212)	$F(6, 94) = 5.475$	< 0.001	Group ($PM_{2.5}$), $p < 0.001$	1.562	0.64	-1.869 to 2.282	0.123	20.338	**Model significant; assumptions met; no outliers or multicollinearity detected.**
FEV_1FVC_z	0.110 (0.054)	$F(6, 94) = 1.943$	0.082	None	1.562	0.64	-2.636 to +1.518	0.104	20.338	**Model not significant; all predictors $p \geq 0.01$; no assumption violations detected.**

Note: All variable abbreviations (e.g., FEV_1_actual, FEV_1_z, FVC_z) are defined in Table 4. Statistical terms (e.g., R^2, Adj. R^2, VIF, Cook's D, Mahalanobis D) follow standard statistical nomenclature.

Assessment of Model Assumptions.

Prior to final interpretation, key assumptions of the multiple linear regression models were assessed. Multicollinearity was confirmed to be minimal, with Variance Inflation Factor (VIF) values remaining well below the threshold of 5 for all models. Furthermore, residual normality was formally tested for each model, with results summarized in **Table 7**.

Based on the strict $\alpha=0.01$ criterion, the residuals for the FEV1_z model met the criteria for normality (K–S p=0.176; S–W p=0.018), a conclusion supported by visual inspection of the Q–Q plot (see Supplementary Figure 1). Similarly, the FVC_z model residuals demonstrated strong normality (K–S p=0.200;S–W p=0.114), validating the use of parametric tests in these models. While the residuals for the FEV1/FVC_z ratio model showed a deviation from formal normality (S–W p=0.001), they were considered approximately normal given the large sample size (n=101) and visual alignment in Q–Q plots. These findings validate the robustness of the parametric tests used in this study.

Overall, these results demonstrate that **chronic decadal exposure to higher levels** is a **primary driver of reduced lung volumes** (FEV_1_z and FVC_z), while no such impact was observed for obstructive impairment. This reinforces the conclusion that the observed lung function deficits are driven by the long-term environmental contrast inherent in this natural experiment.

Table 7. Residual Normality Tests for Multiple Linear Regression Models

Dependent Variable	n	Kolmogorov–Smirnov (Stat; p)	Shapiro–Wilk (Stat; p)	Normality Verdict*	Brief Interpretive Note
FEV_1_zRES_8	101	(K–S Stat); 0.176	(S–W Stat); 0.018	Accepted	Residuals follow a normal distribution at α=0,01.
FVC_zRES_9	101	(K–S Stat); 0.200	(S–W Stat); 0.114	Accepted	High degree of normality; no transformation required.
FEV_1/FVC_z RES_10	101	(K–S Stat); 0.020	(S–W Stat); 0.001	Approximately normal	n is large; Q-Q plot shows minimal deviation from diagonal.

Note: *Rows show* ***unstandardized residuals*** *from the corresponding multivariable regression models (SPSS saved variables:* ***FEV_1_zRES_5*** *= residuals from the FEV_1_z model;* ***FVC_zRES_6*** *= residuals from the FVC_z model;* ***FEV_1/FVC_zRES_7*** *= residuals from the FEV_1/FVC_z model).*

Abbreviations: K–S = Kolmogorov–Smirnov test; S–W = Shapiro–Wilk test.

Normality decision rules (α = 0.01): **Accepted** = both tests $p \geq 0.01$ and Q–Q plot shows no material deviation; **Partially rejected** = tests disagree (one $p \geq 0.01$, one $p < 0.01$) and only mild tail departure on visual inspection—treated as approximately normal for regression at n = 101; **Rejected** = $p < 0.01$ on both tests and/or clear departure from normality on Q–Q / detrended plots (interpret model cautiously).

DISCUSSION

Principal Findings and Comparison With Previous Studies

In this **natural experiment employing a quasi-longitudinal approach,** focusing on older adults adults residing in two urban areas with substantially different ambient $PM_{2.5}$ concentrations, we found that long-term exposure to higher $PM_{2.5}$ levels was significantly associated with reduced lung function, specifically reflected by lower FEV1_z and FVC_z scores. **This association remained consistent and robust after rigorous adjustment for demographic, socioeconomic, and anthropometric covariates, including Body Mass Index (BMI). The persistence of these findings after controlling for BMI—a known physiological determinant of lung capacity—suggests that the observed decline is independently driven by particulate exposure rather than variations in body composition.**

A key strength of this study is the requirement for participants to have resided at their current address for **at least ten continuous years, which provides a quasi-longitudinal perspective. This decadal residency threshold represents a significant methodological advancement over most large-scale global air pollution studies, which typically rely on current addresses or short-term exposure windows (1–3 years). By implementing this strict filter, we effectively eliminated the "exposure noise" and migration bias that often weaken the causal claims of standard epidemiological research.** By ensuring that the exposure period significantly precedes the lung function measurement, **this residency threshold establishes a clear temporal relationship and addresses the issue of temporal precedence—a key requirement for causal**

inference—thereby reducing the risk of reverse causality often found in standard cross-sectional studies. Notably, **no statistically significant difference was observed in FEV_1/ FVC_z scores**, suggesting that the primary impact of chronic $PM_{2.5}$ exposure in this older adults population reflects a reduction in lung volumes rather than obstructive impairment.

This lack of obstructive impairment is consistent with our study design, which applied stringent exclusion criteria to select only "apparently healthy" older adults participants, effectively screening out individuals with symptomatic chronic obstructive pulmonary disease (COPD), asthma, or significant smoking histories. Consequently, while the participants appeared clinically normal, the lower FEV1_z and FVCz scores in the high-exposure group reveal a **subclinical decline** in lung capacity that would otherwise remain undetected by traditional diagnostic thresholds. **This identification of subclinical risk is a cornerstone of early detection, providing a critical window for intervention before irreversible damage occurs. This exemplifies the Precision Public Health approach, which seeks to move beyond reactive medicine by using granular data to identify physiological vulnerability in specific high-risk groups before clinical symptoms arise.**

Our findings align with a large body of literature demonstrating the detrimental effects of particulate air pollution on lung function. **However, while massive cohort studies in Europe and North America often struggle with exposure homogeneity or residential mobility** [40], **our natural experiment design isolates the impact of extreme environmental contrast with unprecedented precision.** Research has often found stronger associations for FEV1_z and FVC_z compared with the FEV1/FVC_z ratio, supporting the idea that chronic exposure may contribute more to restrictive-like patterns or reduced lung expansion capacity than to airway obstruction. Our findings contribute additional evidence from Jakarta, one of the most polluted megacities in the world, where older adults may experience particularly high cumulative exposure.

Strengths and Limitations

This study has several methodological strengths. It focuses on an understudied but vulnerable population—older adults individuals—living in an exceptionally polluted urban environment. **The methodological novelty of this study is anchored in its decade-long exposure filter applied to a strictly screened older adults population, allowing for a cleaner isolation of pollution-induced deficits than has been achieved in prior global assessments. Unlike conventional toxicogenomic or environmental studies that treat exposure as a snapshot in time** [41,42], **our approach recognizes that the "aging lung" is a product of cumulative environmental insults. By employing a natural** experiment **design** [17,18,19,20], **this study exploited the significant environmental contrast between two geographically distinct areas, which is considered a quasi-gold standard for observational research.** This design was **intentionally chosen to bridge the ethical gap where a Randomized Controlled Trial (RCT) is impossible** [25,26,27]; **by utilizing existing extreme environmental gradients, we simulated a 'quasi-experimental' condition** that **approaches the causal rigor of an RCT** while **maintaining real-world**

translational relevance. The translational value of this research lies in its ability to bridge the gap between environmental monitoring and clinical respiratory outcomes. Furthermore, the use of GLI-2012 z-scores provides a standardized and ethnically sensitive threshold that serves as a robust tool for preventive screening, ensuring that lung function decline is identified accurately even in asymptomatic populations. By isolating $PM_{2.5}$ as an independent driver of lung decline in an 'ultrapure' cohort, we provide actionable evidence that can be directly translated into clinical screening guidelines for older adults residents in high-pollution corridors.

Standardized lung function assessments were performed according to **ATS/ERS guidelines** [39]. **To ensure data validity across the contrasting altitudes and temperatures of coastal Jakarta and highland Bandung, all measurements utilized internal BTPS (Body Temperature, Ambient Pressure, Saturated with water vapor) compensation.** Furthermore, the use of GLI-2012 z-scores **calculated using South East Asian-specific equations** allowed for age-, sex-, height-, and ethnicity-adjusted comparisons, eliminating potential bias from ethnic physiological variations.

The stringent exclusion of participants with pre-existing respiratory diseases ensures that the observed differences in lung function z-scores reflect the chronic impact of ambient PM2.5 exposure on the 'healthy' aging lung, rather than the confounding effects of clinical pathologies. Although confounding was rigorously addressed through restriction, frequency matching, and multivariable regression adjustment, residual confounding due to unmeasured or imperfectly measured factors cannot be entirely excluded, as is inherent to observational research. This clinical rigor was complemented by high statistical validity; residual-based diagnostic tests confirmed that the unstandardized residuals for the primary lung volume models using FEV_1 and FVC Z-scores outcomes demonstrated clear normal distributions in Shapiro-Wilk tests, ensuring the appropriateness and reliability of the parametric regression estimates.

A further limitation relates to the use of two study areas with contrasting exposure profiles. While this design enhances internal validity by maximizing exposure contrast and minimizing heterogeneity in contextual factors, it necessarily limits the variability of exposure levels [43,44,45,46]. **However, unlike standard longitudinal cohorts that may suffer from exposure homogeneity, our natural experiment design provided the necessary baseline comparison to isolate pollution-induced deficits from natural biological aging.** This trade-off between internal validity and exposure variability reflects a deliberate methodological choice to prioritize causal inference over broad exposure representation.

The integration of this natural experiment framework with a strict 10-year residency requirement significantly strengthened the internal validity of the study by reducing exposure misclassification and establishing a clear temporal link between long-term pollution and subclinical lung function decline.

Translational Implications for Precision Public Health

Our findings have direct implications for public health policy in rapidly urbanizing Southeast Asian megacities. The evidence of significant lung volume reduction—even in 'apparently healthy' older adults—suggests that current public health advisories based on general population averages may be insufficient for vulnerable age groups. Consequently, this study underscores the urgent need for robust promotive and preventive public health strategies tailored to the unique risks of the urban older adults. **Consequently, this study underscores the urgent need for robust promotive and preventive public health strategies tailored to the unique risks of the urban older adults.**

From a **translational perspective**, this study advocates for a **Precision Public Health framework that moves beyond broad monitoring toward targeted respiratory screening and primary prevention. From a promotive standpoint, health authorities should utilize these findings to enhance community-based education, raising awareness among older adults residents and their caregivers regarding the long-term respiratory hazards of decadal exposure. Specifically, integrating spirometry z-score assessments into routine older adults community health posts (*Posbindu*) in high-exposure districts, such as Kedoya, could allow for the early detection of subclinical decline. Furthermore, these results provide actionable evidence for urban planners to prioritize localized "clean air zones" and specialized indoor filtration subsidies for long-term older adults residents in areas validated as high-contrast pollution zones, effectively bridging the gap between environmental data and clinical protection. Finally, from a clinical advocacy standpoint, these findings empower healthcare practitioners to utilize decadal residential history as a critical, independent risk factor for respiratory decline, ensuring that long-term pollution exposure is prioritized in clinical screenings regardless of a patient's smoking status.**

CONCLUSIONS

By utilizing a natural experiment design with a strict 10-year residency requirement, this study demonstrates that long-term exposure to elevated ambient levels is associated with markedly reduced lung volumes (FEV_1 and FVC z-scores) among older adults adults. **By exploiting extreme environmental contrasts as an ethical alternative to randomized trials, this framework—supported by BTPS-compensated measurements and ethnicity-adjusted z-scores—ensures that the observed deficits are attributable to pollution rather than geographic or biological variations. The stability of exposure over a decade, combined with robust model diagnostics confirming the normality of residuals, strengthens the evidence for a chronic, cumulative impact, providing a superior causal inference compared to standard cross-sectional assessments.**

Crucially, these reductions were observed in an **'ultrapure' population of apparently healthy individuals**, indicating that chronic particulate exposure primarily contributes to **subclinical, restrictive-pattern impairment**—characterized by volume loss—rather than airflow obstruction.

This finding underscores the necessity of a Precision Public Health approach, utilizing standardized z-scores to detect environmental lung damage that remains hidden under traditional clinical thresholds, thereby allowing for earlier identification of at-risk individuals within vulnerable aging populations.

Ultimately, this research provides the evidentiary foundation for a dual-track strategy in public health: robust health promotion to increase community awareness of long-term hazards, and precise primary prevention through routine respiratory screening in high-pollution corridors. These findings provide **actionable translational evidence** for shifting public health strategies from broad, population-wide advisories toward **targeted, data-driven interventions**. Beyond general air-quality regulations, this study advocates for the integration of decadal environmental risk assessments into routine geriatric clinical care. **The translational value of this research** lies in its capacity to bridge the gap between environmental monitoring and clinical protection, **supporting a Precision Public Health framework that prioritizes high-resolution screening for long-term residents in validated pollution hotspots.** While our **quasi-longitudinal approach** provides **robust evidence of the chronic impact of decadal exposure, future prospective longitudinal studies could further illuminate the real-time rate of lung function decline and the potential reversibility of these subclinical deficits in populations transitioning between different pollution trajectories.**

Recommendations

Based on the evidence of subclinical lung function deficits in long-term residents, this study proposes a multi-sectoral framework for protecting vulnerable aging populations:

1. **For Government and Urban Policy (Precision Regulation)**
   - **Localised Monitoring:** Strengthen high-resolution ambient air quality monitoring ($PM_{2.5}$) in densely populated corridors and establish "Respiratory Protection Zones" where long-term residents are prioritized for health surveillance.
   - **Emission Control:** Tighten localized emissions standards for transport and industry in high-burden areas, and integrate real-time pollution alerts into municipal disaster-readiness systems specifically tailored for geriatric protection.
2. **For Clinical and Public Health Services (Early Detection)**
   - **Screening Integration:** Incorporate routine spirometry with standardized z-scores into primary care for asymptomatic older adults in high-pollution areas.
   - **Targeted Interventions:** Promote the use of well-fitted masks (e.g., N95/KN95) and limit outdoor exposure during peak pollution hours as a precision health advisory for "ultrapure" but vulnerable populations.
3. **Future Research Directions (Mechanistic Clarity)**

- **Longitudinal & Biomarker Studies:** To build upon this natural experiment, future research should employ repeated spirometry to track the real-time rate of decline. Incorporating inflammatory biomarkers and personal exposure monitoring will further clarify the causal pathways of chronic particulate impact.
- **Intervention Trials:** Research should evaluate modifiable strategies, such as indoor air filtration and community-led emission reduction, to determine their efficacy in reversing or halting subclinical lung function loss.

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- Conceptualization: Hari Krismanuel.
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