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Examining the Association between Particulate Matter ($PM_{2.5}$) Exposure and Under-five Child Mortality in India Using Cluster-Level Analysis

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Abstract

Background: Fine particulate matter ($PM_{2.5}$) pollution has emerged as a major public health concern linked to several adverse health outcomes among children. Yet, limited evidence exists on its spatial association with under-five child mortality in India at the cluster level. Therefore, this study examines the association between $PM_{2.5}$ exposure and under-five mortality across India using spatial and multivariable analyses.

Methods: The study utilized data from the NFHS-5 (2019-21) linked to NASA's satellite-derived global annual mean $PM_{2.5}$ concentration data at the cluster level. We used bivariate LISA to identify spatial clustering patterns and survey-adjusted multivariable logistic regression models to examine the association between $PM_{2.5}$ exposure and under-five mortality, adjusting for socio-economic, demographic, environmental, and health-related characteristics.

Results: The results indicated a significant spatial clustering of $PM_{2.5}$ concentration and under-five mortality across India. After controlling for confounding factors, every 10 $\mu g/m^3$ increase in $PM_{2.5}$ concentration was associated with 7% higher odds of under-five mortality (AOR: 1.07; 95% CI: 1.04-1.10). Furthermore, children exposed to levels above 80 $\mu g/m^3$ had 40% higher odds of mortality (AOR: 1.40; 95% CI: 1.17-1.67) compared with children exposed to $PM_{2.5}$ levels below 40 $\mu g/m^3$.

Conclusions: The study highlights a significant association between $PM_{2.5}$ exposure and under-five child mortality in India, with substantial spatial heterogeneity in the relationship. Addressing these adverse outcomes requires region-specific public health interventions, improved maternal education, awareness, and environmental policies to reduce air pollution exposure and improve child survival in high-risk areas.

Keywords: Particulate Matter; Under-five mortality; Children; India

Introduction

Globally, air pollution is a leading environmental risk factor for non-communicable diseases and premature death [1,2], which translates into 1 in 10 deaths among under-five children [3]. In 2019, an estimated 99% of the world's population lived in areas where air quality did not meet WHO air quality standards [1]. Notably, 93% of all children breathed air that did not meet WHO safety standards [3]. However, in low- and middle-income countries, which are home to 90% of the world's population, exposure to air pollution has resulted in more than 8 times higher under-5 deaths (41 deaths) than in high-income countries (5 deaths) [4]. In 2024, India is estimated to have 27 deaths per 1000 live births, higher than many South Asian countries, including the Maldives (5 deaths), Sri Lanka (6 deaths), Bhutan (17 deaths), and Nepal (25 deaths) [4].

Under-five mortality is a multifactorial public health outcome influenced by infectious diseases [5,6], neonatal complications [7], and socio-economic disparities [8–11], maternal and child health characteristics and environmental exposure. Among the environmental factors, air pollution has received increasing attention because prolonged exposure to fine particulate matter may adversely affect child survival through multiple biological pathways [12–14]. Research [15] showed that biomass $PM_{2.5}$ and dust $PM_{2.5}$ increase the risk of under-5 mortality by 8.9% and 9.5%, respectively.

Exposure to $PM_{2.5}$ contributes to under-5 mortality by means of prenatal as well as postnatal pathways. For instance, a study [16] found that a 10 $\mu g/m^3$ increase in ambient $PM_{2.5}$ increases the risk of low birth weight by 11% and of preterm birth by 12%, which predispose infants to various fatal health complications. Likewise, a study [17] demonstrated that long-term $PM_{2.5}$ exposure increases the risk of child mortality from acute lower respiratory infections.

A few studies in India [18,19] and elsewhere [12,15,20] documented the association between $PM_{2.5}$ exposure and child mortality. Despite this, there is a significant paucity of evidence in the existing literature regarding the association between $PM_{2.5}$ exposure and under-5 mortality in low- and middle-income countries such as India. First, the existing studies in the Indian setting are not based on the latest dataset. Second, relatively limited attention has been given to the spatial distribution of $PM_{2.5}$ exposure and under-five mortality. Third, previous research has provided limited cluster-level assessment of $PM_{2.5}$ exposure, which is important because exposure may vary considerably across relatively small geographic areas. Additionally, quantitative evidence regarding the association also remains limited and inconsistent. To

address these gaps, the present study provides cluster-level quantitative evidence on the association between $PM_{2.5}$ exposure and under-5 mortality by linking satellite data to the latest round of the Demographic and Health Survey in the Indian context.

Methods

Data Sources

This cross-sectional, cluster-level analytical study examined the association between $PM_{2.5}$ exposure and under-five child mortality in India using data from two sources. The ground-level $PM_{2.5}$ data were obtained from the NASA Earthdata repository, specifically from the Global Annual $PM_{2.5}$ Grids from MODIS, MISR, SeaWiFS and VIIRS Aerosol Optical Depth (AOD), 1998-2022, V5.GL.04 [21]. The under-five mortality data were collected from the fifth round of the National Family Health Survey, conducted in 2019-2021 [22]. A nationally representative cross-sectional survey to demonstrate the association of $PM_{2.5}$ concentration and under-five child mortality in India. The NFHS-5 was executed under the supervision of India's Ministry of Health and Family Welfare (MOHFW), with activity and technical guidance provided by the International Institute of Population Sciences (IIPS), Mumbai, and the Demographic and Health Survey (DHS) [22]. The study used the Kids Recode (KR) file and included 2,32,920 children under 5 years of age in the analysis (**Figure 1**).

Outcome Variable

The dependent variable in this analysis was under-five child mortality in India. Under-five mortality refers to the death of a child before reaching five years of age (0-59 months). The variable was derived from the Kids Recode (KR) file, which contains birth history information collected from women aged 15-49 years. Although NFHS-5 was conducted during 2019–2021, the mortality outcome was not restricted to deaths occurring during the survey period. Instead, it was based on the reported survival status of children included in the birth histories. For the present analysis, the study population was restricted to children born between 2014 and 2021, including those who were reported as deceased at the time of the interview. Children who died before attaining the age of five years were coded as 1= "Child is dead", whereas children who survived beyond five years or were alive at the time of the survey were coded as 0 = "Child is alive". Thus, the outcome variable was treated as a binary variable for the analysis.

Exposure Variable

The primary exposure variable in this study was ambient fine particulate matter $PM_{2.5}$. We obtained annual mean $PM_{2.5}$ concentrations for 2014-2021 from NASA's global gridded $PM_{2.5}$ dataset to assess the association between ambient $PM_{2.5}$ exposure and under-five child mortality. The study population was restricted to children born between 2014 and 2021, based on information on children's date of birth (b3), survival status (b5) and age at death (b7) recorded in the NFHS-5 birth histories, including children who were reported as deceased at the time of the interview. To maintain a consistent exposure definition across the analytical population and align the exposure period with the birth-history period, we used the mean $PM_{2.5}$ concentration across 2014–2021 as the primary exposure measure.

We used geographic coordinates from the standard DHS geocoded dataset for India (NFHS-5, 2019–21) to estimate cluster-level $PM_{2.5}$ exposure. To accommodate the spatial displacement of DHS cluster locations, buffer zones of 2 km for urban clusters and 5 km for rural clusters were created around each survey cluster [23]. We selected these buffer distances based on the DHS spatial sampling framework, which commonly accounts for the greater geographic dispersion of rural populations than urban populations [24]. We then averaged the eight annual cluster-level estimates to derive a single mean $PM_{2.5}$ concentration for each cluster. Finally, we merged mean cluster-level $PM_{2.5}$ values with the children dataset using the cluster identification number (v001) for subsequent analysis.

To assess the robustness of the findings to the choice of $PM_{2.5}$ exposure period, we conducted a sensitivity analysis using an alternative exposure window of 2017 to 2021. We selected the 2017–2021 window to represent a more recent exposure period encompassing the NFHS-5 survey years (2019–2021) and the preceding two years. The results of the sensitivity analysis were presented in Supplementary Table 1.

Based on the mean $PM_{2.5}$ concentration, we examined the exposure level in two ways. First, we treated $PM_{2.5}$ as a continuous variable and estimated the association for each 10 $\mu g/m^3$ increase in $PM_{2.5}$ concentration. Second, we categorised mean $PM_{2.5}$ concentrations into four exposure groups: $\leq$40, 40–60, 60–80, and >80 $\mu g/m^3$. We used the $\leq$40 $\mu g/m^3$ category as the reference group because, according to the Central Pollution Control Board [25], the permissible limit for the annual mean concentration of $PM_{2.5}$ in India is 40 $\mu g/m^3$. This approach allowed us to assess the association between $PM_{2.5}$ exposure and under-five mortality across both continuous and categorised exposure levels.

Covariates and adjustment variables

The study examined the association between $PM_{2.5}$ exposure and under-five child mortality in India. The selection of covariates and adjustment variables was based on a review of existing literature. The selected variables comprised potential confounders and other relevant adjustment covariates, including several socio-demographic, economic, environmental and health-related characteristics. Socio-demographic and economic variables include child age in months (0-11/ 12-23/ 24-35/ 36-47/ 48-59), sex of the child (male/ female), social category (SC/ST/ non-SC/ST), place of residence (rural/ urban), low birth weight (no/yes), place of delivery (home/ institution), maternal BMI (comprised into three categories: Underweight/ Normal/ Overweight), Maternal education level (No education/ Primary/ Secondary/ Higher), ANC visits (no/yes), wealth index (comprised into three categories: Poor/ Middle /Rich), and region (South/ Central/ East/ North-east/ West/ North); Health and environment related variables included maternal smoking behaviour (smokes nothing/ Smoking cigarettes/Tobacco), cooking fuel (clean fuel/ polluting fuel), sources of drinking water (improved/ unimproved), sanitation (improved/ unimproved), season of survey (winter/ summer/ Monsoon/ Post monsoon).

Statistical Analysis

The study first summarised the distribution of the sample population using bivariate descriptive statistics and weighted percentages to assess the association between $PM_{2.5}$ and under-five child mortality in India. Then, bivariate cross-tabulations were used to demonstrate the prevalence of under-five mortality across environmental, socio-economic, demographic, and health characteristics, and Pearson's chi-squared test was used to assess significance.

Univariate LISA was used to visualise the local spatial clustering of $PM_{2.5}$ and under-five mortality across geographic areas. The Univariate Moran's I is given by the following expression.

$$\text{Univariate Moran's I} = \frac{n}{S_o} x \frac{\sum i \sum j W_{ij}(x_i - \bar{X})(x_j - \bar{X})}{\sum i (x_i - \bar{X})^2}$$

where $x_i$and $x_j$denote the values of the study variable at locations $i$and j, respectively, and $\bar{X}$represents the mean value of the variable across all spatial units, n refers to the total number of spatial units included in the analysis, W_{ij}denotes the standardized spatial weight matrix, which specifies the spatial relationship or neighbourhood structure between locations i and j; S_0 represents the sum of all spatial weights and is defined as $S_o = \sum i \sum j W_{ij}$

We used bivariate LISA to assess the spatial autocorrelation between $PM_{2.5}$ exposure and under-five child mortality across cluster points. The bivariate LISA approach is particularly useful for identifying the spatial association between an independent variable and a dependent variable across neighbouring locations. This method enables the detection of localized spatial clusters, including high-high, low-low, high-low, and low-high associations between $PM_{2.5}$ concentration and under-five mortality. The bivariate Moran's I is given by the following expression.

$$\text{Bivariate Moran's I} = \frac{n}{S_o} x \frac{\sum i \sum j W_{ij}(x_i - \bar{X})(y_j - \bar{Y})}{\sum i (y_i - \bar{Y})^2}$$

Where x and y are the explanatory and outcome variables, respectively. $\bar{X}$ and $\bar{Y}$ denotes the mean values of x and y. Here n refers to the total number of spatial units, while W_{ij} represents the standardized spatial weight matrix that defines the spatial relationship or connectivity between locations i and j, with diagonal elements equal to zero. Further, S_o denotes the sum of all spatial weights and is expressed as $S_o = \sum i \sum j W_{ij}$.

In the final stage of the analysis, a multivariable binary logistic regression model was used to examine the association between $PM_{2.5}$ exposure and under-five child mortality, adjusting for socio-economic, demographic, environmental, and health-related covariates. Since the outcome variable was binary in nature, survey-adjusted logistic regression analysis was performed using the "**svy:logistic**" command to account for the complex survey design, including sampling weights, clustering, and stratification. The survey design was specified using the command: "**svyset v021 [pw=wt], strata (v022) singleunit(centred)**". To check multicollinearity among the explanatory variables, we used the Variance Inflation Factor (VIF), and all VIF values were below the acceptable threshold of 5, indicating no significant multicollinearity. We did not apply formal multiple-comparison adjustments, such as Bonferroni or false discovery rate correction. The analyses were primarily hypothesis-driven and focused on estimating the association between $PM_{2.5}$ exposure and under-five mortality. All the statistical analyses were conducted in Stata (v.17), and spatial analyses were performed in GeoDa and ArcGIS.

Results

The spatial distribution of $PM_{2.5}$ and under-five child mortality shows substantial spatial heterogeneity across India. Higher $PM_{2.5}$ concentrations were mostly observed in the Indo-

Gangetic Plain, especially in parts of Uttar Pradesh, Bihar, Delhi, Haryana, and Punjab. In comparison, concentrations were mostly lower in the southern and northeastern regions of the country. The high positive Moran's I value of 0.954 indicates that concentrations were geographically clustered rather than randomly distributed across India (**Figure 2**). Similarly, under-five mortality also appears spatially clustered, as indicated by the univariate Moran's I value of 0.468, with relatively higher child mortality observed in northern and central India (**Figure 3**). The spatial co-occurrence of high $PM_{2.5}$ levels and higher under-five mortality suggests a possible spatial association between air pollution exposure and child health outcomes in India.

We found significant spatial dependence between $PM_{2.5}$ concentration and under-five child mortality across districts in India. **Figure 4** presents the bivariate LISA cluster map and significance map showing the spatial relationship between $PM_{2.5}$ concentration and under-five child mortality across the 707 districts of India. The analysis reveals a significant positive spatial autocorrelation between $PM_{2.5}$ exposure and under-five child mortality, as indicated by the positive Moran's I value of 0.389. This suggests that districts with higher $PM_{2.5}$ concentrations tend to be spatially associated with districts exhibiting higher levels of under-five child mortality. Among the 707 districts, 82 were identified as significant high-high clusters (hotspots), representing areas where high under-five mortality was spatially associated with high $PM_{2.5}$ concentrations, predominantly in the Indo-Gangetic plain regions, including parts of Uttar Pradesh, Madhya Pradesh, Bihar, and surrounding states of India. In contrast, 102 districts were identified as significant low-low clusters (cold spots), indicating areas where lower levels of under-five child mortality were spatially associated with lower $PM_{2.5}$ concentrations.

Table 1 presents the environmental, socio-demographic, maternal, and household-level characteristics of the children aged 0-59 months. Among the total sample population, 3.74% of the under-five children had died. Approximately 73% of the sample children lived in areas where the annual mean $PM_{2.5}$ concentration exceeded the National Ambient Air Quality Standards (NAAQS) safety threshold of 40 $\mu g/m^3$, indicating widespread exposure to elevated ambient particulate matter pollution. Most children were male (51.96%), in the 48-59 months age group (20.94%), from non-SC/ST communities (64.79%), residing in rural areas (73.35%), and had normal birth weight (83.47%). Most of the children were born to mothers who delivered in institutional health facilities (88.8%), had a normal body mass index (BMI) (61.48%), and had completed secondary education (50.69%). Approximately 19% of mothers

attended 8 or more ANC visits. Nearly 46% of the children belonged to households in the poorest wealth quintile, and 3.32% of the children belonged to households where mothers reported smoking cigarettes or tobacco. About half of the children (49.9%) lived in households using polluting cooking fuels, while 4.21% and 26.93% lived in households with unimproved drinking water sources and sanitation facilities, respectively. The larger proportion of the children resided in the central region (27.88%). Furthermore, most surveys were conducted in the winter (36.06%) and monsoon (30.28%) seasons.

Table 2 represents the prevalence of under-five mortality across selected environmental, socio-demographic, maternal, and household-level characteristics in India. Our study observed a clear exposure gradient across the $PM_{2.5}$ categories. The prevalence of under-five mortality increased progressively with rising $PM_{2.5}$ concentrations, from 2.62% among children residing in areas with $PM_{2.5}$ levels below 40 $\mu g/m^3$ to 5.11% among those living in areas with $PM_{2.5}$ concentrations exceeding 80 $\mu g/m^3$. This finding suggests a highly significant positive association ($p < 0.001$) between particulate matter exposure and under-five child mortality.

The study also found that children aged 36 to 47 months (4.13%), male children (3.97%), those belonging to the SC/ST category (4.38%), those residing in rural regions (3.98%), and those with low birth weight (5.84%) had a higher prevalence of under-five mortality. Furthermore, a higher prevalence of under-five mortality was observed among children born to mothers who delivered at home (5.73%), had a below-normal body mass index (BMI) (3.83%), had no formal education (5.42%), did not attend at least eight ANC visits (2.74%) and mothers who smoked cigarettes or Tobacco (5.32%). Moreover, children belonging to the household with the poor wealth quintile (4.81%), using polluting cooking fuel (4.56%), and with unimproved sanitation facilities (4.84%) observed a higher prevalence of under-five mortality. Children who belong to the central part of India had a higher proportion of under-five mortality, and this association was also statistically significant (5.09%). However, children with a higher prevalence of under-five mortality were observed among those children who were surveyed during winter (4.20%) and summer (4.42%) seasons.

Table 3 presents the results of the multivariable logistic regression examining the association between $PM_{2.5}$ and under-five child mortality, adjusted for sociodemographic, maternal, household, and environmental characteristics. After adjusting for selected covariates, the findings indicate that in adjusted model 1, every 10 $\mu g/m^3$ increase in $PM_{2.5}$ concentration was associated with 7% higher odds of under-five mortality (AOR: 1.07; 95% CI: 1.04-1.10). The

sensitivity analysis using the alternative 2017–2021 exposure period showed a similar pattern of results (**Supplementary Table 1**). In model 2, children exposed to higher $PM_{2.5}$ concentrations generally had higher odds of under-five mortality than those exposed to ≤40 µg/m³, although the association for the 40–60 µg/m³ category was not statistically significant. Children exposed to 60–80 µg/m³ had 32% higher odds of under-five mortality (AOR: 1.32; 95% CI: 1.12–1.55), while those exposed to >80 µg/m³ had 40% higher odds (AOR: 1.40; 95% CI: 1.17–1.67) compared with children exposed to ≤40 µg/m³.

The probability of under-five mortality was significantly lower with increasing age (AOR: 0.59; 95% CI: 0.51-0.68). Male children (AOR: 1.10; 95% CI: 1.01-1.20), those belonging to the SC/ST community (AOR: 1.13; 95% CI: 1.03-1.24) and those with low birth weight (AOR: 1.89; 95% CI: 1.71-2.09) had a higher probability of under-five mortality. Children born to mothers who delivered their children in a home facility (AOR: 1.25; 95% CI: 1.11-1.42), mothers with an overweight BMI (AOR: 1.30; 95% CI: 1.15-1.46), and those who smoked cigarettes/tobacco (AOR: 1.32; 95% CI: 1.10-1.58) were significantly higher odds of under-five mortality compared with children in their respective reference categories. However, children born to mothers with higher educational attainment (AOR: 0.46; 95% CI: 0.37-0.56), attended 8 or more ANC visits (AOR: 0.73; 95% CI: 0.62-0.86) and were born to mothers in richer wealth quintiles (AOR: 0.73; 95% CI: 0.62-0.86) had a significantly lower likelihood of under-five mortality.

Children from households using polluting cooking fuel (AOR: 1.11; 95% CI:0.99-1.25), with unimproved drinking water (AOR: 1.03; 95% CI: 0.85-1.24), unimproved sanitation facilities (AOR: 1.04; 95% CI: 0.94-1.15), those children were surveyed in winter season (AOR: 1.12; 95% CI: 0.96-1.31) and children who resided in the central region of India (AOR: 1.08; 95% CI: 0.85-1.37) had higher odds of under-five mortality; however, this association was not statistically significant.

Discussion

The present study revealed that nearly one-fifth of the children (18.20%) were exposed to >80 µg/m^3 $PM_{2.5}$ concentration, which is twice the level of the National Ambient Air Quality Standard (40 µg/m^3) and sixteen times greater than the WHO Air Quality Standard (5 µg/m^3) [26]. Additionally, annual mean $PM_{2.5}$ concentrations were particularly high across the Indo-Ganga Plain, and under-5 mortality was also concentrated in the same region. The study findings also showed a consistent positive association between $PM_{2.5}$ exposure and under-5

mortality, with a 7% increase in the risk of under-5 mortality per 10 µg/m³ increase in $PM_{2.5}$ concentration. However, the share was higher than prior estimates in India [19], but lower elsewhere [27].

The positive spatial association (Bivariate Local Moran's I: 0.389) between $PM_{2.5}$ and under-five child mortality was found across districts in Uttar Pradesh, parts of Madhya Pradesh, Bihar, Jharkhand, and Chhattisgarh. This may reflect the combined influence of environmental, socioeconomic, demographic and healthcare-related factors. These regions are characterised by persistently elevated ambient air pollution, driven by multiple sources, including biomass and solid-fuel consumption, vehicular emissions, industrial activities, construction-related dust, agricultural residue burning, and seasonal meteorological conditions that can limit pollutant dispersion [28]. In addition, several of these areas experience socioeconomic deprivation, including poor household and sanitation conditions, limited access to maternal and child healthcare practices [11], which may interact with environmental exposure and contribute to spatial variation in under-five child mortality.

Multivariable logistic regression revealed that after controlling for covariates, under-5 mortality positively increased with increasing $PM_{2.5}$ exposure, with children exposed to >80 µg/m^3 having 40% greater odds of mortality. The findings were consistent with previous studies [15,20,27] while contradicting a study [29], which reported no significant association. Against this backdrop, the association between $PM_{2.5}$ exposure and under-5 child mortality could be explained on the grounds of respiratory problems. Studies in India [30,31] and elsewhere [32,33] have shown a positive association between $PM_{2.5}$ exposure and acute respiratory infection (ARI). Additionally, $PM_{2.5}$ exposure is also linked to cardiovascular diseases [34], which also lead to child mortality. The detrimental effects of $PM_{2.5}$ exposure, viz. oxidative stress, systemic inflammation, impaired vascular function, and type 2 diabetes [35,36], which are common among adults, may similarly affect children with prior cardiovascular conditions.

Notably, the risk of under-five mortality decreases significantly with increasing child's age and was consistent with studies in Bangladesh [37]. The plausible reason is that younger children were more vulnerable to infections and other health problems [38,39]. As children grow, vaccinations, better nutrition, and stronger immunity help protect them from illness and reduce their risk of death [40,41] . Similarly, male children had a higher likelihood of under-5 mortality, which was corroborated by studies in Ethiopia [42], Ghana [43]. This male

disadvantage is linked to biological and genetic factors that contribute to a weaker immune system, predisposing male children to infections [44,45]. Contrarily, the findings contradicted a multicountry study [46] that reported excess female under-5 mortality compared to male counterparts and could be credited to gender bias deeply rooted in socio-cultural practices [47–49]. Alongside, SC/ST children had a 13% greater risk of under-5 mortality than their non-SC/ST counterparts. This aligned with an Indian study [10], which demonstrated differences in the level of educational attainment and wealth quintile as a major contributor to the caste-based gap in under-5 mortality. Low birth weight children had a higher probability of under-5 mortality, and it was consistent with previous studies conducted in India [50]. One possible reason is that low birth weight can cause complications such as breathing difficulties and impaired physical growth, which can significantly reduce children's survival probability [51,52].

Notably, children delivered at home had 25% greater odds of under-5 mortality, which is consistent with studies in India [53] and elsewhere [54]. A study [55] showed that the utilisation of maternal healthcare services, such as antenatal care and institutional deliveries, can avert 3 million newborn deaths. Maternal BMI was also a significant determinant of under-5 mortality. For instance, children born to underweight mothers had a 17% lower likelihood, whereas those born to overweight mothers had 30% greater odds of mortality. This finding was consistent with another study [56]. A study by Johansson et.al. [57] revealed that maternal overweight increases the risk of infant mortality due to birth asphyxia and susceptibility to other neonatal morbidities in term births and the increasing occurrence of preterm birth. Mothers who attended eight or more ANC visits had their children have a 27% lower probability of under-five mortality. Frequent ANC visits provide more opportunities to receive TT injections and IFA supplements, which serve as protective components against neonatal mortality [58]. Apparently, maternal education and wealth quintile were negatively associated with under-five mortality. For instance, children born to women who completed higher education and belonged to the highest wealth quintile had 54% and 27% lower odds of mortality, respectively, corroborated by other studies in India [59,60] and elsewhere [43,61]. A study in Bangladesh [62] showed that maternal education averts child mortality by delaying marriage and associated delays in childbearing, reducing fertility, improving health-related knowledge, and fostering better health-seeking behaviours. Additionally, educated and wealthier mothers are more likely to ensure proper child nutrition [63,64] and adopt hygiene practices [65] that improve child survival. Maternal smoking increased the odds of under-5 mortality by 32% and was in tune

with a prior study [66], which documented a 71% higher risk of infant mortality and a 99% higher risk of mortality among the children aged 12-59 months having combined exposure to maternal smoking and polluting fuel. This could be linked to the increased risk of ARI, bronchiolitis, asthma, and bacterial meningitis among under-5 children with exposure to maternal smoking [67]. However, after adjustment for potential confounders, polluting cooking fuel was not statistically significantly associated with under-5 mortality in this study. Similarly, children living in households with unimproved drinking water and sanitation had a 3% and 4% higher likelihood of under-5 mortality, although this association was not statistically significant in the adjusted model. Research [6,68] showed that poor sanitation is often linked to diarrhoea and nematode infections, which cause 3.5 million under-5 deaths every year.

Policy Implications

The study's policy implications are as follows. Firstly, positive spatial autocorrelation between $PM_{2.5}$ levels and under-five mortality across the Indo-Gangetic plains underscores the need for integrated environmental and child health policies, particularly in Uttar Pradesh, parts of Madhya Pradesh, Bihar, Jharkhand, and Chhattisgarh. These findings support strengthening the implementation of India's National Clean Air Programme (NCAP), which provides a national framework for reducing particulate-matter pollution through coordinated national, state, and city-level action plans. In areas identified as $PM_{2.5}$ and under-five mortality hotspots, NCAP-related interventions can be reinforced with targeted air-quality monitoring, source-specific emission-control measures, and community-level risk communication. Another existing policy, like POSHAN, needs to widen its scope by integrating air-pollution risk communication and community-level counselling into routine ANC and PNC follow-ups by ASHA workers. The findings also support promoting the sustained use of clean cooking fuels through Pradhan Mantri Ujjwala Yojana (PMUY), alongside multi-sectoral emission-control measures in areas with high $PM_{2.5}$ exposure. Secondly, the study also suggests a target group approach for addressing vulnerable groups such as mothers who delivered their children in home facilities, did not attend eight or more ANC visits, and children who belong to the socioeconomically deprived groups.

Limitations

While this study provides important evidence, several limitations warrant consideration. First, the cross-sectional design precludes establishing a causal relationship between $PM_{2.5}$ exposure and under-five mortality. Second, $PM_{2.5}$ exposure was measured at the cluster level and may

not accurately capture individual-level exposure. Because DHS clusters are spatially displaced to protect respondent confidentiality, the assigned $PM_{2.5}$ exposure may not accurately reflect individual children's actual locations. This may result in exposure misclassification, particularly in areas with substantial spatial variation or steep gradients in $PM_{2.5}$ concentrations. Moreover, the present study did not incorporate environmental determinants such as land surface temperature, annual precipitation, LULC and wind speed. Therefore, further study is required to capture environmental determinants of the profile of particulate matter and under-five child mortality.

Conclusions

This study examined the association between exposure to particulate matter air pollutants and under-five child mortality in India using cluster-level data from nationally representative surveys. In our study, higher $PM_{2.5}$ exposure was significantly associated with an elevated risk of under-five mortality after adjustment for socio-economic, demographic, environmental, and health-related characteristics. This indicates that children living in environmentally vulnerable and socio-economically deprived regions face a disproportionately higher mortality burden. Therefore, air pollution represents not only an environmental challenge but also a significant public health concern for child health outcomes in India. The study highlights the need for urgent, integrated policy interventions focusing on ambient air pollution, improved household living conditions, enhanced maternal education and sanitation awareness, and reducing regional-level disparities. In addition, targeted environmental and public health interventions in high-risk clusters can make a significant contribution to India's Sustainable Development Goals (SDGs) on child survival and health equity.

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Author Contributions

TG, **PD**, **PC**, and **MR** conceptualised the study and performed the formal analysis. **TG**, **PD**, and **PC** interpreted the findings, prepared the initial manuscript draft, and contributed to the revision of subsequent versions. All authors critically reviewed the manuscript and approved the final version for publication.

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Data availability

This study utilized publicly available secondary data on children under five years of age obtained from the Demographic and Health Surveys (DHS) Programme (https://dhsprogram.com/data/available-datasets.cfm). $PM_{2.5}$ concentration data were obtained from the NASA Earth Data Repository and are publicly available for research purposes (https://www.earthdata.nasa.gov).

Declarations

Ethics approval and consent to participate

Since the study uses secondary data, no ethical approval is required.

Consent for publication

Not applicable

Competing interests

The authors declare no competing interests.

Clinical trial number

Not applicable

Human ethics and consent to participate

Not applicable

References

1. WHO. Ambient (outdoor) air pollution [Internet]. World Health Organization. 2024 [cited 2026 Jun 1]. https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health. Accessed 1 Jun 2026

2. Landrigan PJ, Fuller R, Acosta NJR, Adeyi O, Arnold R, Basu N (Nil), et al. The Lancet Commission on pollution and health. The Lancet [Internet]. Elsevier; 2018 [cited 2026 Jun 1];391:462–512. https://doi.org/10.1016/S0140-6736(17)32345-0

3. WHO. More than 90% of the world's children breathe toxic air every day [Internet]. World Health Organization. 2018 [cited 2026 Jun 1]. https://www.who.int/news/item/29-10-2018-more-than-90-of-the-worlds-children-breathe-toxic-air-every-day? Accessed 1 Jun 2026

4. World Bank. Mortality rate, under-5 (per 1,000 live births) [Internet]. 2024. https://data.worldbank.org/indicator/SH.DYN.MORT. Accessed 1 Jun 2026

5. Perin J, Mulick A, Yeung D, Villavicencio F, Lopez G, Strong KL, et al. Global, regional, and national causes of under-5 mortality in 2000–19: an updated systematic analysis with implications for the Sustainable Development Goals. Lancet Child Adolesc Health [Internet]. Elsevier B.V.; 2022 [cited 2026 Jun 1];6:106–15. https://doi.org/10.1016/S2352-4642(21)00311-4

6. UNICEF. Childhood diseases [Internet]. 2021 [cited 2026 Jun 1]. https://www.unicef.org/health/childhood-diseases. Accessed 1 Jun 2026

7. Liu L, Chu Y, Oza S, Hogan D, Perin J, Bassani DG, et al. National, regional, and state-level all-cause and cause-specific under-5 mortality in India in 2000–15: a systematic analysis with implications for the Sustainable Development Goals. Lancet Glob Health [Internet]. Elsevier Ltd; 2019 [cited 2026 Jun 1];7:e721–34. https://doi.org/10.1016/S2214-109X(19)30080-4

8. Kumar C, Piyasa, Saikia N. An update on explaining the rural-urban gap in under-five mortality in India. BMC Public Health [Internet]. BioMed Central; 2022 [cited 2026 Jun 1];22:2093. https://doi.org/10.1186/s12889-022-14436-7

9. Bhusal MK, Khanal SP. A Systematic Review of Factors Associated with Under-Five Child Mortality. Roldan-Valadez E, editor. Biomed Res Int [Internet]. John Wiley & Sons, Ltd; 2022 [cited 2026 Jun 1];2022:1181409. https://doi.org/10.1155/2022/1181409

10. Bora JK, Raushan R, Lutz W. The persistent influence of caste on under-five mortality: Factors that explain the caste-based gap in high focus Indian states. Joe W, editor. PLoS One [Internet]. Public Library of Science; 2019 [cited 2026 Jun 1];14:e0211086. https://doi.org/10.1371/journal.pone.0211086

11. Bora JK. Factors explaining regional variation in under-five mortality in India: An evidence from NFHS-4. Health Place [Internet]. Pergamon; 2020 [cited 2026 Jun 1];64:102363. https://doi.org/10.1016/j.healthplace.2020.102363

12. Amir-ud-Din R, Kumar R, Naeem N, Khan M. Air pollution and under-5 child mortality: linking satellite and IPUMS-DHS data across 41 countries in South Asia and Sub-Saharan Africa. BMC Public Health [Internet]. BioMed Central; 2024 [cited 2026 Jun 1];24:2996. https://doi.org/10.1186/s12889-024-20476-y

13. Bickton FM, Ndeketa L, Sibande GT, Nkeramahame J, Payesa C, Milanzi EB. Household air pollution and under-five mortality in sub-Saharan Africa: an analysis of 14 demographic and health surveys. Environ Health Prev Med [Internet]. BioMed Central; 2020 [cited 2026 Jun 1];25:67. https://doi.org/10.1186/s12199-020-00902-4

14. Lelieveld J, Haines A, Pozzer A. Age-dependent health risk from ambient air pollution: a modelling and data analysis of childhood mortality in middle-income and low-income

502 countries. Lancet Planet Health [Internet]. Elsevier B.V.; 2018 [cited 2026 Jun 1];2:e292–
503 300. https://doi.org/10.1016/S2542-5196(18)30147-5

504 15. Owili PO, Lin T-H, Muga MA, Lien W-H. Impacts of discriminated PM2.5 on global
505 under-five and maternal mortality. Sci Rep [Internet]. Nature Publishing Group; 2020 [cited
506 2026 Jun 1];10:17654. https://doi.org/10.1038/s41598-020-74437-7

507 16. Ghosh R, Causey K, Burkart K, Wozniak S, Cohen A, Brauer M. Ambient and household
508 PM2.5 pollution and adverse perinatal outcomes: A meta-regression and analysis of
509 attributable global burden for 204 countries and territories. Bhutta ZA, editor. PLoS Med
510 [Internet]. Public Library of Science; 2021 [cited 2026 Jun 1];18:e1003718.
511 https://doi.org/10.1371/journal.pmed.1003718

512 17. Arlington L, Patel AB, Simmons E, Kurhe K, Prakash A, Rao SR, et al. Duration of solid
513 fuel cookstove use is associated with increased risk of acute lower respiratory infection
514 among children under six months in rural central India. Dunea D, editor. PLoS One
515 [Internet]. Public Library of Science; 2019 [cited 2026 Jun 1];14:e0224374.
516 https://doi.org/10.1371/journal.pone.0224374

517 18. deSouza PN, Dey S, Mwenda KM, Kim R, Subramanian SV, Kinney PL. Robust
518 relationship between ambient air pollution and infant mortality in India. Science of The Total
519 Environment [Internet]. Elsevier; 2022 [cited 2026 Jun 1];815:152755.
520 https://doi.org/10.1016/j.scitotenv.2021.152755

521 19. Liao J, Liu Y, Steenland K, Pillarisetti A, Thompson LM, Dey S, et al. Child Survival and
522 Early Lifetime Exposures to Ambient Fine Particulate Matter in India: A Retrospective
523 Cohort Study. Environ Health Perspect [Internet]. Public Health Services, US Dept of Health
524 and Human Services; 2022 [cited 2026 Jun 1];130:017009. https://doi.org/10.1289/EHP8910

525 20. He C, Liu C, Chen R, Meng X, Wang W, Ji J, et al. Fine particulate matter air pollution
526 and under-5 children mortality in China: A national time-stratified case-crossover study.
527 Environ Int [Internet]. Pergamon; 2022 [cited 2026 Jun 1];159:107022.
528 https://doi.org/10.1016/j.envint.2021.107022

529 21. NASA. Global Annual PM2.5 Grids from MODIS, MISR, SeaWiFS and VIIRS Aerosol
530 Optical Depth (AOD), 1998-2022, V5.GL.04 - Earthdata Search [Internet]. [cited 2026 Jun
531 1]. https://search.earthdata.nasa.gov/search/granules?p=C3540908987-
532 ESDIS&pg[0][v]=f&pg[0][qt]=2013-01-01T00%3A00%3A00.000Z%2C2020-12-
533 31T23%3A59%3A59.999Z&pg[0][gsk]=-
534 start_date&q=Global%20Monthly%20PM2.5%20grids&qt=2018-05-
535 01T00%3A00%3A00.000Z%2C2019-01-
536 31T23%3A59%3A59.999Z%2C121%2C31&lat=37.414221735729626&long=102.90897119
537 65706&zoom=3.4363739265726605. Accessed 1 Jun 2026

538 22. International Institute for Population Sciences (IIPS) and ICF. National Family Health
539 Survey (NFHS 5), 2019-2021: India: Volume II [Internet]. Mumbai; 2021.
540 https://dhsprogram.com/pubs/pdf/FR375/FR375_II.pdf. Accessed 12 Oct 2024

23. Sarkar D, Kumar A, Imam F, Ghosh S, Marshall JD, Apte J, et al. Contrasting Patterns in Ambient PM2.5 Exposure Disparity Across Population Subgroups in Urban and Rural India. Geohealth [Internet]. John Wiley and Sons Inc; 2026 [cited 2026 Jun 1];10:e2025GH001387. https://doi.org/10.1029/2025GH001387

24. Perez-Heydrich C, Warren JL, Burgert CR, Emch ME. Influence of Demographic and Health Survey Point Displacements on Raster-Based Analyses. Spat Demogr [Internet]. Springer; 2016 [cited 2026 Sep 24];4:135–53. https://doi.org/10.1007/s40980-015-0013-1

25. CPCB. National Ambient Air Quality Standards [Internet]. 2009. https://cpcb.gov.in/uploads/National_Ambient_Air_Quality_Standards.pdf. Accessed 24 Sep 2026

26. WHO. WHO Global Air Quality Guidelines 2021 [Internet]. 2021. https://iiasa.ac.at/sites/default/files/2025-02/WHO%20global%20air%20quality%20guidelines%202021_%20Setting%20ambitious%20goals%20for%20air%20quality%20to%20protect%20public%20health.pdf. Accessed 24 Sep 2026

27. Heft-Neal S, Burney J, Bendavid E, Burke M. Robust relationship between air quality and infant mortality in Africa. Nature [Internet]. Nature Publishing Group; 2018 [cited 2026 Jun 1];559:254–8. https://doi.org/10.1038/s41586-018-0263-3

28. Pandey A, Brauer M, Cropper ML, Balakrishnan K, Mathur P, Dey S, et al. Health and economic impact of air pollution in the states of India: the Global Burden of Disease Study 2019. Lancet Planet Health [Internet]. Elsevier B.V.; 2021 [cited 2026 Sep 24];5:e25–38. https://doi.org/10.1016/S2542-5196(20)30298-9

29. Goyal N, Karra M, Canning D. Early-life exposure to ambient fine particulate air pollution and infant mortality: pooled evidence from 43 low- and middle-income countries. Int J Epidemiol [Internet]. Oxford Academic; 2019 [cited 2026 Jun 1];48:1125–41. https://doi.org/10.1093/ije/dyz090

30. Adhikary M, Mal P, Saikia N. Exploring the link between particulate matter pollution and acute respiratory infection risk in children using generalized estimating equations analysis: a robust statistical approach. Environmental Health [Internet]. BioMed Central; 2024 [cited 2026 Jun 1];23:12. https://doi.org/10.1186/s12940-024-01049-3

31. George PE, Thakkar N, Yasobant S, Saxena D, Shah J. Impact of ambient air pollution and socio-environmental factors on the health of children younger than 5 years in India: a population-based analysis. The Lancet Regional Health - Southeast Asia [Internet]. Elsevier Ltd; 2024 [cited 2026 Jun 1];20:100328. https://doi.org/10.1016/j.lansea.2023.100328

32. Wu Y, Jin T, He W, Liu L, Li H, Liu C, et al. Associations of fine particulate matter and constituents with pediatric emergency room visits for respiratory diseases in Shanghai, China. Int J Hyg Environ Health [Internet]. Urban & Fischer; 2021 [cited 2026 Jun 1];236:113805. https://doi.org/10.1016/j.ijheh.2021.113805

33. Kim K-N, Kim S, Lim Y-H, Song IG, Hong Y-C. Effects of short-term fine particulate matter exposure on acute respiratory infection in children. Int J Hyg Environ Health [Internet]. Urban & Fischer; 2020 [cited 2026 Jun 1];229:113571. https://doi.org/10.1016/j.ijheh.2020.113571

34. Luo R, Dai H, Zhang Y, Wang P, Zhou Y, Li J, et al. Association of short-term exposure to source-specific PM2.5 with the cardiovascular response during pregnancy in the Shanghai MCPC study. Science of The Total Environment [Internet]. Elsevier; 2021 [cited 2026 Jun 1];775:145725. https://doi.org/10.1016/j.scitotenv.2021.145725

35. Riggs DW, Zafar N, Krishnasamy S, Yeager R, Rai SN, Bhatnagar A, et al. Exposure to airborne fine particulate matter is associated with impaired endothelial function and biomarkers of oxidative stress and inflammation. Environ Res [Internet]. Academic Press; 2020 [cited 2026 Jun 1];180:108890. https://doi.org/10.1016/j.envres.2019.108890

36. Lao XQ, Guo C, Chang L, Bo Y, Zhang Z, Chuang YC, et al. Long-term exposure to ambient fine particulate matter (PM2.5) and incident type 2 diabetes: a longitudinal cohort study. Diabetologia [Internet]. Springer; 2019 [cited 2026 Jun 1];62:759–69. https://doi.org/10.1007/s00125-019-4825-1

37. Abir T, Agho KE, Page AN, Milton AH, Dibley MJ. Risk factors for under-5 mortality: evidence from Bangladesh Demographic and Health Survey, 2004–2011. BMJ Open [Internet]. British Medical Journal Publishing Group; 2015 [cited 2026 Sep 24];5:e006722. https://doi.org/10.1136/bmjopen-2014-006722

38. Imran MIK, Inshafi MUA, Sheikh R, Chowdhury MAB, Uddin MJ. Risk factors for acute respiratory infection in children younger than five years in Bangladesh. Public Health [Internet]. W.B. Saunders; 2019 [cited 2026 Sep 24];173:112–9. https://doi.org/10.1016/j.puhe.2019.05.011

39. Varghese JS, Muhammad T. Prevalence, potential determinants, and treatment-seeking behavior of acute respiratory infection among children under age five in India: Findings from the National Family Health Survey, 2019-21. BMC Pulm Med [Internet]. BioMed Central; 2023 [cited 2026 Sep 24];23:195. https://doi.org/10.1186/s12890-023-02487-4

40. Black RE, Victora CG, Walker SP, Bhutta ZA, Christian P, de Onis M, et al. Maternal and child undernutrition and overweight in low-income and middle-income countries. The Lancet [Internet]. Elsevier B.V.; 2013 [cited 2026 Sep 24];382:427–51. https://doi.org/10.1016/S0140-6736(13)60937-X

41. Shattock AJ, Johnson HC, Sim SY, Carter A, Lambach P, Hutubessy RCW, et al. Contribution of vaccination to improved survival and health: modelling 50 years of the Expanded Programme on Immunization. The Lancet [Internet]. Elsevier B.V.; 2024 [cited 2026 Sep 24];403:2307–16. https://doi.org/10.1016/S0140-6736(24)00850-X

42. Fikru C, Getinet M, Shaweno T. Proximate Determinants of Under-Five Mortality in Ethiopia: Using 2016 Nationwide Survey Data. Pediatric Health Med Ther [Internet].

Informa UK Limited; 2019 [cited 2026 Jun 1];10:169–76. https://doi.org/10.2147/PHMT.S231608

43. Iddrisu A-K, Boanyo E. Survival analysis of under-five mortality and associated risk factors using survival analysis approaches. Gajbhiye R, editor. PLOS Global Public Health [Internet]. Public Library of Science; 2025 [cited 2026 Jun 1];5:e0005179. https://doi.org/10.1371/journal.pgph.0005179

44. Drevenstedt GL, Crimmins EM, Vasunilashorn S, Finch CE. The rise and fall of excess male infant mortality. Proceedings of the National Academy of Sciences [Internet]. National Academy of Sciences; 2008 [cited 2026 Jun 1];105:5016–21. https://doi.org/10.1073/pnas.0800221105

45. WELLS JCK. Natural Selection and Sex Differences in Morbidity and Mortality in Early Life. J Theor Biol [Internet]. Academic Press; 2000 [cited 2026 Jun 1];202:65–76. https://doi.org/10.1006/jtbi.1999.1044

46. Costa JC, da Silva ICM, Victora CG. Gender bias in under-five mortality in low/middle-income countries. BMJ Glob Health [Internet]. BMJ Publishing Group Ltd; 2017 [cited 2026 Jun 1];2:e000350. https://doi.org/10.1136/bmjgh-2017-000350

47. Diamond-Smith N, Bishai D. Evidence of Self-correction of Child Sex Ratios in India: A District-Level Analysis of Child Sex Ratios From 1981 to 2011. Demography [Internet]. Duke University Press; 2015 [cited 2026 Jun 1];52:641–66. https://doi.org/10.1007/s13524-014-0356-z

48. Park JJ, Brondi L. Why are girls still dying unnecessarily? The need to address gender inequity in child health in the post–2015 development agenda. J Glob Health [Internet]. University of Edinburgh; 2015 [cited 2026 Jun 1];5:020303. https://doi.org/10.7189/jogh.05.020303

49. Ram U, Jha P, Ram F, Kumar K, Awasthi S, Shet A, et al. Neonatal, 1–59 month, and under-5 mortality in 597 Indian districts, 2001 to 2012: estimates from national demographic and mortality surveys. Lancet Glob Health [Internet]. Elsevier; 2013 [cited 2026 Jun 1];1:e219–26. https://doi.org/10.1016/S2214-109X(13)70073-1

50. Jana A, Saha UR, Reshmi RS, Muhammad T. Relationship between low birth weight and infant mortality: evidence from National Family Health Survey 2019-21, India. Archives of Public Health [Internet]. BioMed Central; 2023 [cited 2026 Sep 24];81:28. https://doi.org/10.1186/s13690-023-01037-y

51. Karande S. Consequences of low birth weight, maternal illiteracy and poor access to medical care in rural India: infantile iatrogenic Cushing syndrome. BMJ Case Rep [Internet]. BMJ Case Rep; 2015 [cited 2026 Sep 24];2015:bcr2015211387. https://doi.org/10.1136/bcr-2015-211387

52. Xiao X, Zhang Z-X, Li W-H, Feng K, Sun Q, Cohen HJ, et al. Low birth weight is associated with components of the metabolic syndrome. Metabolism [Internet]. W.B. Saunders; 2010 [cited 2026 Sep 24];59:1282–6. https://doi.org/10.1016/j.metabol.2009.12.001

53. Das U, Chaplot B, Azamathulla HM. The Role of Place of Delivery in Preventing Neonatal and Infant Mortality Rate in India. Geographies [Internet]. Multidisciplinary Digital Publishing Institute; 2021 [cited 2026 Jun 1];1:47–62. https://doi.org/10.3390/geographies1010004

54. Ajaari J. Impact Of Place Of Delivery On Neonatal Mortality In Rural Tanzania. Value in Health [Internet]. Elsevier BV; 2013 [cited 2026 Jun 1];16:A209–10. https://doi.org/10.1016/j.jval.2013.03.1059

55. Requejo J, Merialdi M, Althabe F, Keller M, Katz J, Menon R. Born Too Soon: Care during pregnancy and childbirth to reduce preterm deliveries and improve health outcomes of the preterm baby. Reprod Health [Internet]. BioMed Central; 2013 [cited 2026 Jun 1];10:S4. https://doi.org/10.1186/1742-4755-10-S1-S4

56. Huo N, Zhang K, Wang L, Wang L, Lv W, Cheng W, et al. Association of Maternal Body Mass Index With Risk of Infant Mortality: A Dose-Response Meta-Analysis. Front Pediatr [Internet]. Frontiers Media S.A.; 2021 [cited 2026 Jun 1];9:650413. https://doi.org/10.3389/fped.2021.650413

57. Johansson S, Villamor E, Altman M, Bonamy A-KE, Granath F, Cnattingius S. Maternal overweight and obesity in early pregnancy and risk of infant mortality: a population based cohort study in Sweden. BMJ [Internet]. British Medical Journal Publishing Group; 2014 [cited 2026 Jun 1];349:g6572–g6572. https://doi.org/10.1136/bmj.g6572

58. Singh A, Pallikadavath S, Ram F, Alagarajan M. Do antenatal care interventions improve neonatal survival in India? Health Policy Plan [Internet]. Oxford Academic; 2014 [cited 2026 Sep 24];29:842–8. https://doi.org/10.1093/heapol/czt066

59. Meitei WB, Singh A, Ladusingh L. The effects of community clustering on under-five mortality in India: a parametric shared frailty modelling approach. Genus [Internet]. SpringerOpen; 2022 [cited 2026 Jun 1];78:18. https://doi.org/10.1186/s41118-022-00165-7

60. Mandal S, Chouhan P. Maternal Education and Child Mortality Differentials: An Upshot From the National Family Health Survey 2015–2016, India. OMEGA - Journal of Death and Dying [Internet]. SAGE Publications Inc.; 2021 [cited 2026 Jun 1];84:348–59. https://doi.org/10.1177/0030222819860407

61. Balaj M, York HW, Sripada K, Besnier E, Vonen HD, Aravkin A, et al. Parental education and inequalities in child mortality: a global systematic review and meta-analysis. The Lancet [Internet]. Elsevier B.V.; 2021 [cited 2026 Jun 1];398:608–20. https://doi.org/10.1016/S0140-6736(21)00534-1

690 62. Wu H. The Effect of Maternal Education on Child Mortality in Bangladesh. Popul Dev
691 Rev [Internet]. John Wiley and Sons Inc; 2022 [cited 2026 Jun 1];48:475–503.
692 https://doi.org/10.1111/padr.12467

693 63. Tan L, Shahid M, Song J, Muhammad Naveed H, Khan I. Wealth and regional disparities
694 in child undernutrition: insights from national demographic and health survey. Front Public
695 Health [Internet]. Frontiers Media SA; 2025 [cited 2026 Jun 1];13:1654403.
696 https://doi.org/10.3389/fpubh.2025.1654403

697 64. Chinnakotla B, Susarla SM, Mohan DC, Turton B, Husby HM, Morales CP, et al.
698 Associations between Maternal Education and Child Nutrition and Oral Health in an
699 Indigenous Population in Ecuador. Int J Environ Res Public Health [Internet].
700 Multidisciplinary Digital Publishing Institute; 2022 [cited 2026 Jun 1];20:473.
701 https://doi.org/10.3390/ijerph20010473

702 65. Sen P, Habib MA, Rahman T, Chowdhury AI, Karim KMR. Exploring Gaps in Maternal
703 WASH Practices: A Cross-Sectional KAP Study in Rural Coastal Bangladesh. Public Health
704 Challenges [Internet]. John Wiley and Sons Ltd; 2025 [cited 2026 Jun 1];4:e70171.
705 https://doi.org/10.1002/puh2.70171

706 66. Akinyemi JO, Adedini SA, Wandera SO, Odimegwu CO. Independent and combined
707 effects of maternal smoking and solid fuel on infant and child mortality in sub-Saharan
708 Africa. Tropical Medicine & International Health [Internet]. Blackwell Publishing Ltd; 2016
709 [cited 2026 Jun 1];21:1572–82. https://doi.org/10.1111/tmi.12779

710 67. Lawder R, Whyte B, Wood R, Fischbacher C, Tappin DM. Impact of maternal smoking
711 on early childhood health: a retrospective cohort linked dataset analysis of 697 003 children
712 born in Scotland 1997–2009. BMJ Open [Internet]. British Medical Journal Publishing
713 Group; 2019 [cited 2026 Jun 1];9:e023213. https://doi.org/10.1136/bmjopen-2018-023213

714 68. WHO. Diarrhoea: Why children are still dying and what can be done [Internet]. World
715 Health Organization. 2009 [cited 2026 Jun 1].
716 https://www.who.int/publications/i/item/9789241598415. Accessed 1 Jun 2026

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721 **Table 1:** Background Characteristics of the sample population

Background Characteristics	Unweighted Frequency	Weighted Percentage	95% CI
Under-Five Child Mortality			
No	2,24,218	96.26	96.14-96.37
Yes	8,702	3.74	3.63-3.85

$PM_{2.5}$ ($\mu g/m^3$)			
≤40	78,407	27.57	27.38-27.76
40-60	61,507	29.48	29.28-29.67
60-80	44,894	24.76	24.58-24.94
>80	28,955	18.20	18.04-18.36
Child's age in months			
0 to 11	46,378	19.93	19.72-20.15
12 to 23	45,042	19.44	19.23-19.64
24 to 35	45,978	19.78	19.57-19.99
36 to 47	46,513	19.91	19.69-20.14
48 to 59	49,009	20.94	20.73-21.15
Sex of the Child			
Female	1,12,255	48.04	47.76-48.32
Male	1,20,665	51.96	51.68-52.24
Social Category			
SC/ST	94,966	35.21	34.70-35.72
Non-SC/ST	1,25,666	64.79	64.28-65.30
Place of Residence			
Rural	1,85,721	73.35	72.87-73.82
Urban	47,199	26.65	26.18-27.13
Place of Delivery			
Home	31,609	11.2	10.93-11.47
Institution	2,01,311	88.8	88.53-89.07
Low Birth Weight			
No	1,96,485	83.47	83.32-83.62
Yes	36,435	16.53	16.38-16.68
Maternal BMI			
Underweight	42,431	19.44	19.12-19.76
Normal	1,43,833	61.48	61.11-61.85
Overweight	40,470	19.08	18.77-19.39
Maternal Education Level			
No Education	51,210	21.36	21.01-21.71
Primary	30,081	12.32	12.07-12.56
Secondary	1,19,864	50.69	50.28-51.10
Higher	31,765	15.64	15.28-16.00
ANC visit (8 or above)			
No	143,113	80.51	80.32-80.70
Yes	31,370	19.49	19.30-19.68
Wealth Index			
Poor	1,17,869	46.32	45.86-46.78
Middle	45,083	19.53	19.22-19.86
Rich	69,968	34.14	33.69-34.61
Maternal Smoking Behaviour			
Smokes Nothing	2,17,952	96.68	96.55-96.80
Smoking Cigarettes/Tobacco	14,968	3.32	3.20-3.45
Cooking Fuel			

Clean fuel	99,284	50.1	49.63-50.58
Polluting Fuel	1,22,315	49.9	49.42-50.37
Sources of Drinking Water			
Improved	2,06,529	95.79	95.61-95.96
Unimproved	15,320	4.21	4.04-4.39
Sanitation			
Improved	1,63,775	73.07	72.63-73.50
Unimproved	58,073	26.93	26.50-27.37
Season of Survey			
Winter	74,521	30.06	29.64-30.49
Summar	37,173	15.66	15.32-16.00
Monsoon	64,205	30.28	29.82-30.76
Post Monsoon	57,021	24	23.54-24.45
Region			
South	29,269	16.52	16.20-16.85
Central	60,560	27.88	27.52-28.24
East	45,227	26.13	25.74-26.52
North-East	34,222	3.63	3.55-3.72
West	20,552	12.44	12.03-12.86
North	43,090	13.4	13.15-13.65

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724 **Table 2:** Prevalence of Mortality among the Under-five children in India, 2019-2021

Background Characteristics	Under-five Child Mortality		p value
	No (n=224218)	Yes (n=8702)	
$PM_{2.5}$ (µg/m^3)			<0.001
≤40	97.38	2.62	
40-60	96.59	3.41	
60-80	95.62	4.38	
>80	94.89	5.11	
Child's age in months			<0.001
0 to 11	96.69	3.31	
11 to 23	96.38	3.62	
24 to 35	96.17	3.83	
36 to 47	95.87	4.13	
48 to 59	96.19	3.81	
Sex of the Child			<0.001
Female	96.51	3.49	
Male	96.03	3.97	
Social Category			<0.001
SC/ST	95.62	4.38	
Non-SC/ST	96.55	3.45	
Place of Residence			<0.001

Rural	96.02	3.98	
Urban	97.21	2.79	
Place of Delivery			<0.001
Home	94.27	5.73	
Institution	96.51	3.49	
Low Birth Weight			<0.001
No	96.67	3.33	
Yes	94.16	5.84	
Maternal BMI			<0.001
Underweight	96.17	3.83	
Normal	96.18	3.82	
Overweight	96.52	3.48	
Maternal Education Level			<0.001
No Education	94.58	5.42	
Primary	95.42	4.58	
Secondary	96.64	3.36	
Higher	97.97	2.03	
ANC visit (8 or above)			<0.001
No	97.26	2.74	
Yes	98.48	1.52	
Wealth Index			<0.001
Poor	95.19	4.81	
Middle	96.49	3.51	
Rich	97.57	2.43	
Maternal Smoking Behaviour			<0.001
Smokes Nothing	96.31	3.69	
Smoking Cigarettes/Tobacco	94.68	5.32	
Cooking Fuel			<0.001
Clean fuel	97.11	2.89	
Polluting Fuel	95.44	4.56	
Sources of Drinking Water			0.159
Improved	96.29	3.71	
Unimproved	95.8	4.2	
Sanitation			<0.001
Improved	96.68	3.32	
Unimproved	95.16	4.84	
Season of Survey			<0.001
Winter	95.8	4.2	
Summer	95.58	4.42	
Monsoon	96.7	3.3	
Post Monsoon	96.72	3.28	
Region			<0.001
South	97.69	2.31	
Central	94.91	5.09	
East	95.96	4.04	
North-East	96.74	3.26	

West	97.21	2.79	
North	96.87	3.13	

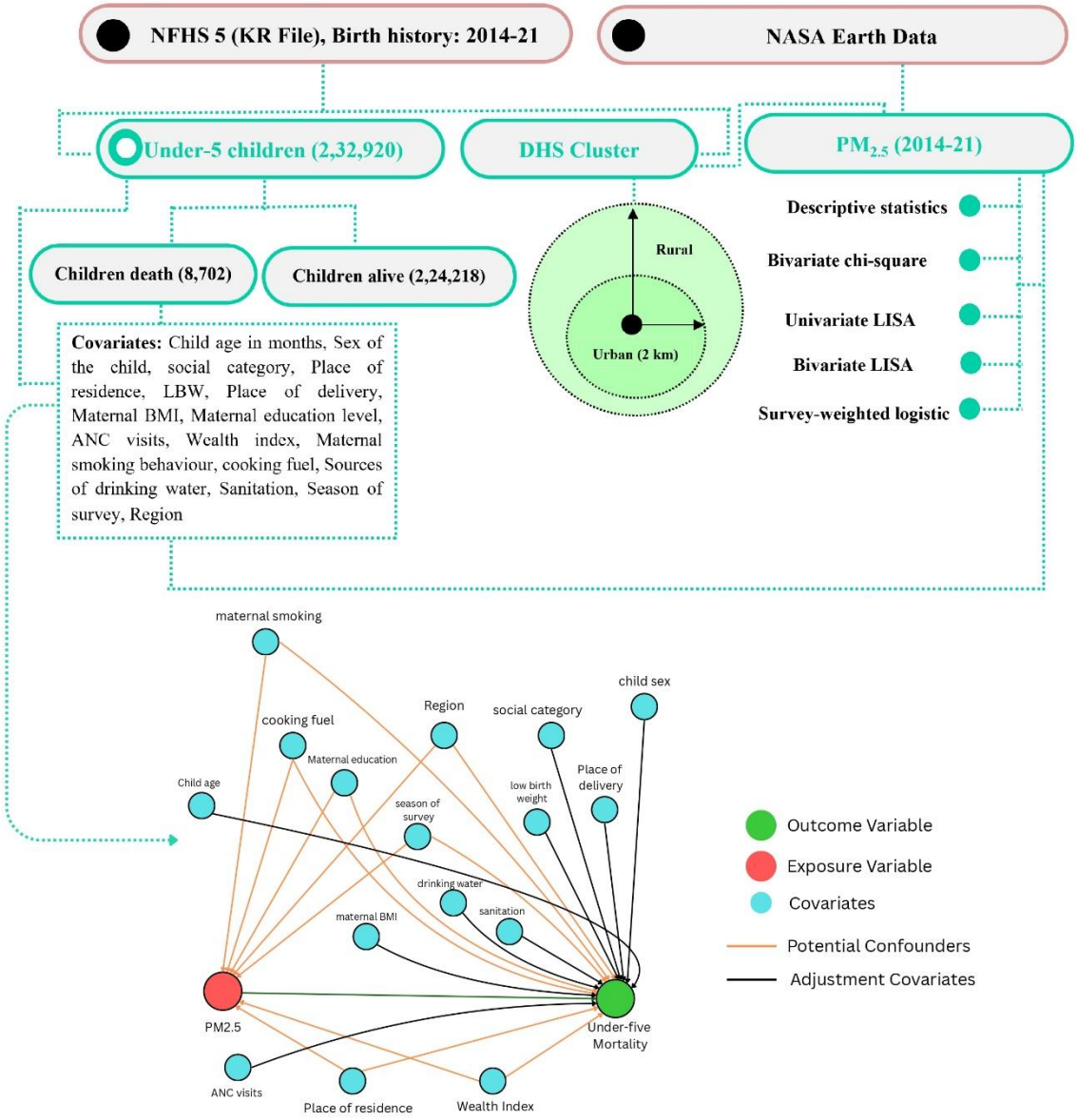
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726 **Table 3:** Multivariable Survey Logistic regression results showing the association between
727 $PM_{2.5}$ and Under Five child Mortality in India, 2019-21

Background Characteristics	OR	AOR	AOR
		Model 1	Model 2
$PM_{2.5}$ (every 10 µg/m^3 increase)	1.12*** (1.11-1.4)	1.07*** (1.04-1.10)	-
$PM_{2.5}$ (µg/m^3)			
≤40	**Ref.**		**Ref.**
40-60	1.31*** (1.20-1.43)	-	1.08 (0.93-1.26)
60-80	1.70*** (1.55-1.85)	-	1.32** (1.12-1.55)
>80	2.00*** (1.82-2.19)	-	1.40*** (1.17-1.67)
Child's age in months			
0 to 11	**Ref.**	**Ref.**	**Ref.**
11 to 23	1.10 (0.99-1.21)	0.82** (0.73-0.92)	0.82** (0.73-0.92)
24 to 35	1.16** (1.06-1.27)	0.67*** (0.58-0.76)	0.67*** (0.59-0.76)
36 to 47	1.26*** (1.15-1.38)	0.65*** (0.57-0.75)	0.65*** (0.57-0.75)
48 to 59	1.16** (1.06-1.27)	0.59*** (0.51-0.68)	0.59*** (0.51-0.68)
Sex of the Child			
Female	**Ref.**	**Ref.**	**Ref.**
Male	1.14*** (1.08-1.21)	1.10* (1.01-1.20)	1.10* (1.01-1.20)
Social Category			
SC/ST	1.28*** (1.21-1.36)	1.13** (1.03-1.24)	1.13** (1.03-1.24)
Non-SC/ST	**Ref.**	**Ref.**	**Ref.**
Place of Residence			
Rural	1.45*** (1.32-1.60)	0.97 (0.84-1.12)	0.97 (0.84-1.12)
Urban	**Ref.**	**Ref.**	**Ref.**
Place of Delivery			
Home	1.68*** (1.55-1.82)	1.25*** (1.11-1.42)	1.25*** (1.11-1.42)
Institution	**Ref.**	**Ref.**	**Ref.**
Low Birth Weight			
No	Ref.	**Ref.**	**Ref.**
Yes	1.80*** (1.68-1.93)	1.89*** (1.71-2.09)	1.89*** (1.71-2.09)
Maternal BMI			
Underweight	1.00 (0.93-1.08)	0.83** (0.74-0.93)	0.83** (0.74-0.92)
Normal	**Ref.**	**Ref.**	**Ref.**
Overweight	0.91* (0.83-0.99)	1.30*** (1.15-1.46)	1.30*** (1.15-1.46)
Maternal Education Level			
No Education	**Ref.**	**Ref.**	**Ref.**
Primary	0.84*** (0.76-0.92)	0.84* (0.73-0.96)	0.84* (0.73-0.97)
Secondary	0.61*** (0.57-0.65)	0.67*** (0.60-0.74)	0.67*** (0.60-0.74)
Higher	0.36*** (0.31-0.43)	0.46*** (0.37-0.56)	0.46*** (0.37-0.56)

ANC visit (8 or above)			
No	Ref.	Ref.	Ref.
Yes	0.55*** (0.48-0.63)	0.74*** (0.63-0.86)	0.73*** (0.62-0.86)
Wealth Index			
Poor	**Ref.**	**Ref.**	**Ref.**
Middle	0.72*** (0.66-0.78)	0.89 (0.77-1.01)	0.89 (0.77-1.01)
Rich	0.49*** (0.45-0.54)	0.73*** (0.62-0.86)	0.73*** (0.62-0.86)
Maternal Smoking Behaviour			
Smokes Nothing	**Ref.**	**Ref.**	**Ref.**
Smoking Cigarettes/tobacco	1.47*** (1.30-1.66)	1.32** (1.10-1.58)	1.32** (1.10-1.58)
Cooking Fuel			
Clean fuel	**Ref.**	**Ref.**	**Ref.**
Polluting Fuel	1.60*** (1.50-1.72)	1.12 (0.99-1.26)	1.11 (0.99-1.25)
Sources of Drinking Water			
Improved	**Ref.**	**Ref.**	**Ref.**
Unimproved	1.14* (1.00-1.30)	1.02 (0.85-1.24)	1.03 (0.85-1.24)
Sanitation			
Improved	**Ref.**	**Ref.**	**Ref.**
Unimproved	1.48*** (1.39-1.58)	1.04 (0.94-1.15)	1.04 (0.94-1.15)
Season of Survey			
Winter	1.28*** (1.19-1.39)	1.11 (0.95-1.29)	1.12 (0.96-1.31)
Summar	1.35*** (1.24-1.48)	1.09 (0.92-1.29)	1.11 (0.93-1.32)
Monsoon	**Ref.**	**Ref.**	**Ref.**
Post Monsoon	0.99 (0.90-1.10)	1.04 (0.89-1.20)	1.04 (0.90-1.21)
Region			
South	**Ref.**	**Ref.**	**Ref.**
Central	2.27*** (2.03-2.53)	1.05 (0.83-1.33)	1.08 (0.85-1.37)
East	1.78*** (1.58-2.00)	0.88 (0.71-1.10)	0.91 (0.72-1.14)
North-East	1.42*** (1.23-1.65)	0.96 (0.76-1.23)	0.97 (0.76-1.24)
West	1.21** (1.01-1.45)	0.88 (0.70-1.12)	0.92 (0.72-1.17)
North	1.37*** (1.20-1.55)	0.82 (0.65-1.04)	0.85 (0.67-1.08)
Constant		***0.03*** (0.02-0.04)***	***0.03*** (0.02-0.04)***
Design df		***23,737***	***23,737***
F		***(30, 23708) 26.35***	***(32, 23706) 25.10***
Prob > F		***<0.001***	***<0.001***
Mean VIF for AOR model		***1.72***	***1.79***

****p<0.001, **p<0.01, *p<0.05*



732

733 **Figure 1.** Conceptual framework of the study

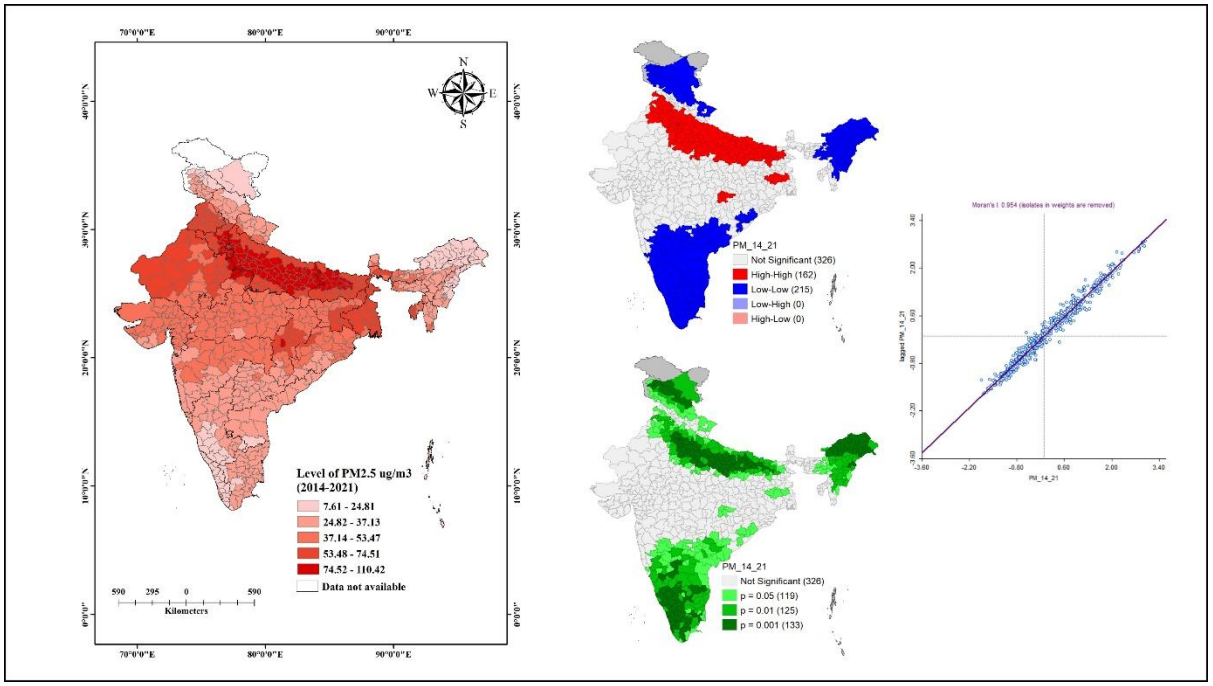


Figure 2. District-wise mean $PM_{2.5}$ concentration in India during 2014–2021, along with univariate LISA cluster and significance maps and the corresponding Moran's I plot

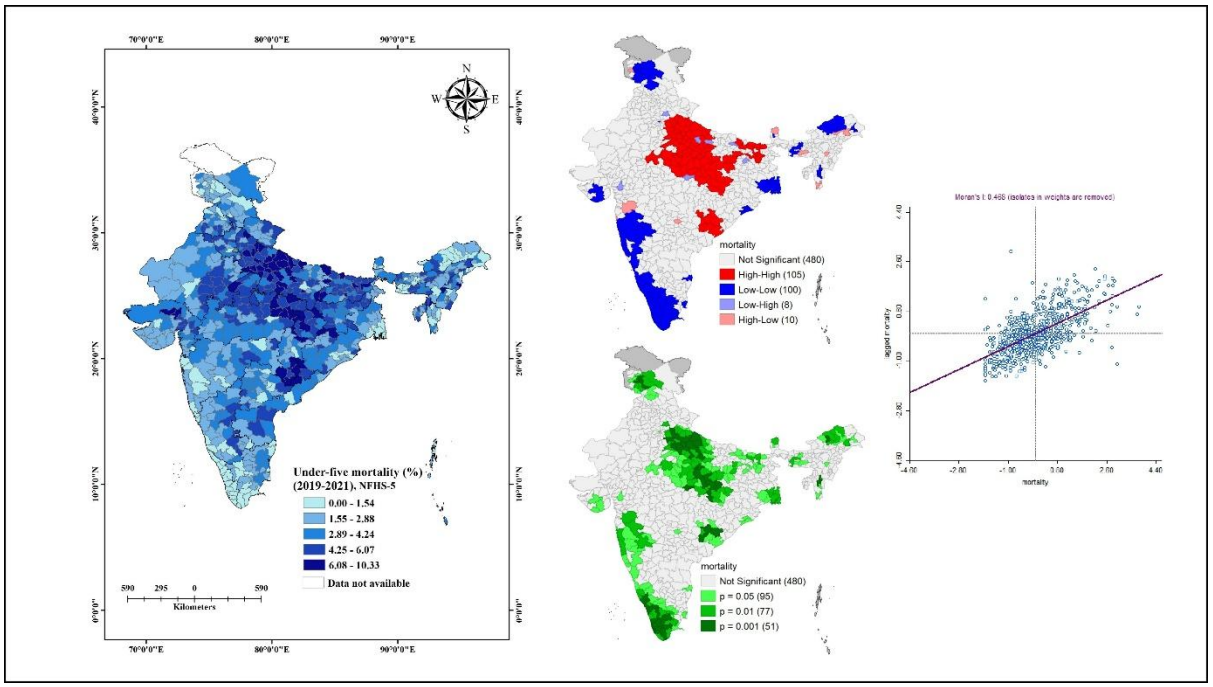
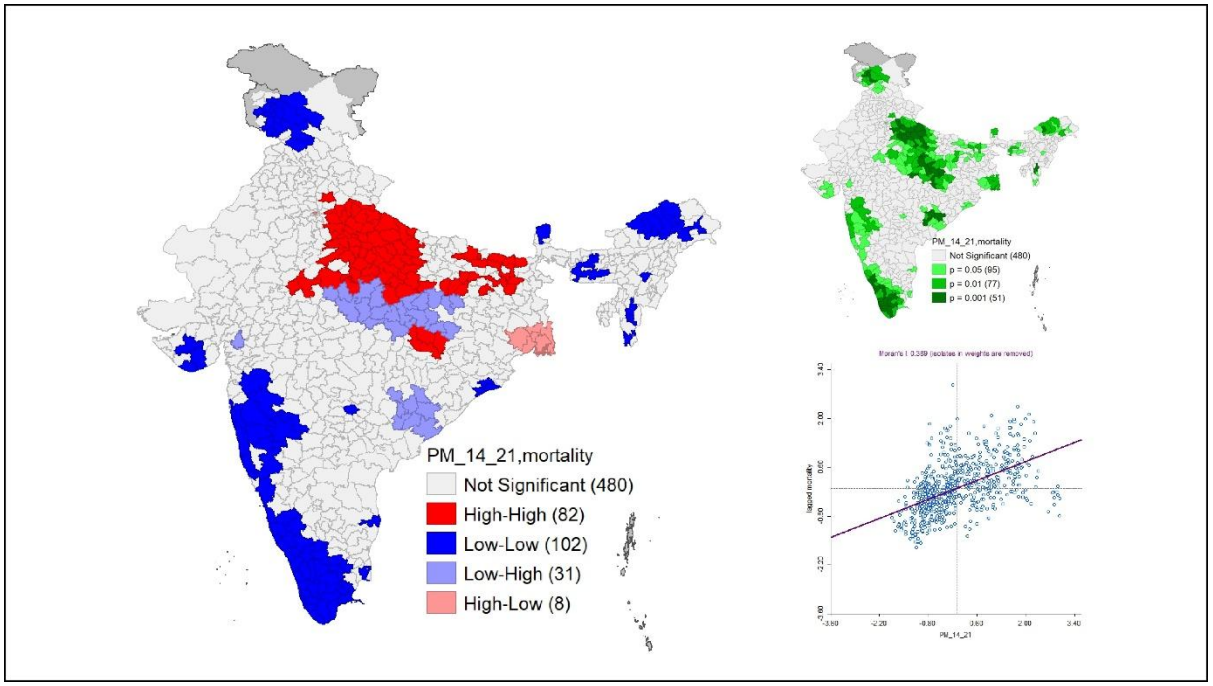


Figure 3. District-wise under-five mortality (%) concentration in India, NFHS 5 (2019–2021), along with univariate LISA cluster and significance maps and the corresponding Moran's I plot.



744

745 **Figure 4.** Bivariate LISA and significance map illustrating the spatial association between
746 $PM_{2.5}$ concentration and under-five child mortality in India.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryTable1.docx