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Effect of exposure to PM_{10} on child health: evidence based on a large-scale survey from 184 cities in India

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ABSTRACT

Introduction Air pollution is increasingly becoming a serious global public health concern. Prior studies examining the effect of air pollution on health have ignored the role of households' hygienic practices and socioeconomic condition, which are key determinants of the health status of a country like India. This study examines the effects of air pollution, measured in levels of particulate matters of size below 10 µg/m^3 (PM_{10}), on child-health outcomes after adjusting for hygiene practices.
Methods Health data from the National Family Health Survey-4 (NFHS-4) and PM_{10} levels provided by the Central Pollution Control Board were matched for 184 Indian towns/cities. Child health outcomes included neonatal mortality, post-neonatal mortality, premature births, children with symptoms of acute respiratory infections (ARI) and low birth weight. Multilevel mixed-effects models were used to estimate the risk associated with exposure to PM_{10}.
Result Analyses based on 23 954 births found that every 10-unit increase in PM_{10} level, increased the risk of neonatal mortality by 6% (adjusted RR (95% CI): 1.02 (1.02 to 1.09)), and the odds of symptoms of ARI among children by 7% (adjusted OR (95% CI): 1.07 (1.03 to 1.12)), and premature births by 8% (adjusted OR (95% CI): 1.08 (1.03 to 1.12)). There was no statistically significant difference in the effect of PM_{10} on child health regardless of household's hygienic practices. Effects of PM_{10} on child health outcomes remained similar for cities whether or not they were part of the National Clean Air Program (NCAP).
Conclusion Exposure to PM_{10}, regardless of hygienic practices, increases the risk of adverse child health outcomes. Study findings suggest that the focus of mitigating the effects of air pollution should be beyond the towns/cities identified under NCAP. Given the increasing industrialisation and urbanisation, a systemic, coherent approach is required to address the issue of air pollution in India.

Key questions

What is already known?

► Effect of air pollution on child health has been examined, mostly limited to a few metro cities, using mathematical models under several assumptions or satellite data. Further, empirical studies though adjusted socioeconomic status and hygiene, have ignored they interplay with the effect of air pollution on child health.

What are the new findings?

► Analysis based on 184 cities/towns of India found that exposure to both poor hygiene and air pollution increase the risk of adverse child health; however, hygiene does not act as an effect modifier. Moreover, these effects were almost homogeneous in National Clean Air Program (NCAP) and non-NCAP cities.

What do the new findings imply?

► Improved sanitation combined with clean air can prevent loss of several newborn lives. Focus on reducing air pollution should not be limited to only selected number of towns; second and third tier towns where industrialisation and urbanisation are happening fast should also be prioritised by the government.

INTRODUCTION

Air pollution is one of the biggest public health concerns of this decade.[1–4] India is globally recognised as a country that has one of the worst air quality, with levels of air pollution increasing annually in metro and non-metro cities.[5–9] A recent report suggests that in 2015 more than one million deaths in India were due to exposure to particulate matters (PM).[10] In 2016, air pollution was identified as the second-largest risk factor contributing to the disease burden in India after malnutrition.[11] As per the global burden of disease study 2017 for India, air pollution contributed to 8% of the total burden of disease, with approximately 0.67 million deaths associated with outdoor air pollution and 0.48 million with indoor air pollution.[12] While poor air quality impacts all, certain age groups are considered more vulnerable, and children are one such group.[13–15] Air pollution not only affects children after birth, but also during the fetal development stage.[13–16]

The sources of harmful pollutants such as $PM_{2.5}$ (PM of size below 2.5 µg/m^3) and PM_{10} (PM of size below 10 µg/m^3) in India are primarily coal combustion, transport, agricultural stubble burning and emissions from household burning for cooking and heating.[15 17] Empirical research suggests that PM of small size fractions are considered to be particularly detrimental to public health as they can enter the respiratory system and lead to respiratory disease, asthma, strokes, cancer and heart disease.[18 19]

There have been ample of researches examining how various individual, societal and environmental factors affect child health outcomes.[4 8 13 14 16 17 20 21] While these studies have documented the mechanisms in which individual and societal factors interact to worsen child health outcomes, there is a dearth of such evidence when it comes to interaction that includes environmental factors. It has been well documented that both exposure to air pollution and poor hygiene practices affect child health; however, there is a dearth of evidence to suggest what would be the joint effect on child health. More importantly, whether household hygiene acts as an effective modifier or as a confounder to the effect of air pollution. A review of studies examining the effects of air pollution on human health in India highlighted that barring a few studies,[17 20] the rest examine the issue in silos, failing to consider other important predictors such as household socioeconomic status or hygiene practices of families.[21] This paper hypothesises that air pollution will continue to have a significant effect on child health outcomes as found by earlier studies regardless of hygienic condition. Another aspect of existing literature is the focus of analysis being limited only to select cities in India. This has limited the decision-making ability of the Government of India. One of the reasons behind this could be that earlier studies have tried to study the effect of $PM_{2.5}$, which is monitored at fewer stations than PM_{10}. To expand the scope of analysis and include more cities and towns in the analysis, this paper considers PM_{10} as the measure of air pollution. This will help in examining the effect of air pollution on child health at the pan-India level when adjusted for socioeconomic status and family hygiene practices. The Government of India launched the National Clean Air Program (NCAP) in 2019 across 110 cities/towns to prevent, control and reduce air pollution.[22] A pan-India analysis would help in assessing how the effects of air pollution on child health vary between towns/cities prioritised by NCAP and those not under NCAP.

METHODS

Data

For this study, two sources of data were linked to measure the effect of PM_{10} exposure on various child health outcomes: (1) National Family Health Survey-4 (NFHS-4) and (2) air quality data.

National Family Health Survey-4

The NFHS is the Indian version of the Demographic and Health Survey (DHS) and is conducted at regular intervals to generate information on various fertility, mortality, family planning and child health indicators at the district, state and national level. The fourth round of NFHS was conducted in 2015/2016 and 699 686 women were interviewed (rural: 494 951 and urban: 204 735) in the 15 to 49 age group covering 601 509 households across all states and union territories of India. The women were recruited through a stratified two-stage sampling process. In the first stage, primary sampling units (PSUs) were selected systematically using a probability proportional size to approach and a fixed number of households and eligible women were selected within the PSUs. In rural areas, a village was considered as the PSU, whereas in urban areas it was a census enumeration block. The detailed sampling procedure is published elsewhere.[23]

Air quality

This paper uses PM_{10} levels data provided by the Central Pollution Control Board (CPCB) released by the Government of India as part of the National Data Sharing and Accessibility Policy.[24] The study considered recorded levels of PM_{10} available in 2015 for 207 towns to align with NFHS data collection. It did not consider the PM_{10} data available for earlier years, as PM_{10} data were not consistently available for preceding years. For the year 2015, first monthly average was computed using the daily PM_{10} data available for every month. The average of monthly PM_{10} estimates was then calculated to arrive at the annual levels of $PM_{10.}$ A comparison of PM_{10} levels for 2015 against the preceding 4 years (2011 to 2014) suggests that they are highly correlated, and levels of PM_{10} recorded in 2015 were likely to be similar in earlier years (figure 1).

Matching air quality data with NFHS-4

The matching of air quality data with NFHS was done based on the district/town names available in both data sources. Following the box-model approach, the study

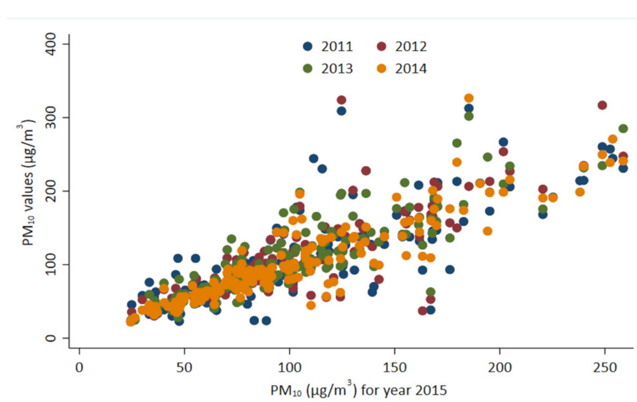

Figure 1 Association between the annual PM_{10} values for 2011 to 2015 for 184 districts in India; Central Pollution Control Board. PM_{10},particulate matters of size below 10 µg/m^3.

assumed that individuals located in a district are equally exposed to PM_{10} level.[25 26] In scenarios where the name of the town in CPCB data was not an exact match with the district name in NFHS-4, the study used the geographical address/location of the town in which the CPCB monitoring site was located to find the district name. Of the 207 districts/towns for which PM_{10} data were available in 2015, PM_{10} levels were available for fewer than 6 months for 23 towns and hence were excluded from the analysis to ensure adequate accuracy in estimating levels of annual PM_{10}. The remaining 184 districts/towns covered 24 states and 3 union territories of India. Also, 95 of these 184 districts/towns have been identified as priority districts under the NCAP. Given that PM_{10} data is only available for urban areas, NFHS-4 observations for rural areas were removed. Following this, for the analysis, household cases with twin births were removed. This resulted in an analytical sample of 23 954 births among 19 000 women.

Measures

The study assessed the effect of PM_{10} on five child health indicators: premature births, neonatal mortality, post-neonatal mortality, experience of acute respiratory infection (ARI) symptoms among children and low birth weight among children. Any birth taking place before 9 months of pregnancy was considered as premature birth. Any child dying within 28 days of birth was considered a neonatal death. Deaths of children after 28 days of birth and before 365 days of birth were considered post-neonatal deaths. Living children under the age of five with the symptoms of short, rapid breathing that was chest-related and/or difficulty in breathing in the 2 weeks preceding the survey were considered to have symptoms of ARI. The rates of premature births, neonatal mortality, post-neonatal mortality and ARI symptoms were estimated per 1000 live births. A child weighing less than 2500 g at the time of birth was defined as having a low birth weight. Hygiene of households was assessed based on their source of drinking water, type of toilet facility, handwashing practices and faecal disposal method of children under the age of five. A household was classified as hygienic if the source of drinking water was improved, the toilet facility used was improved (as per WHO classification), the handwashing place had both water and soap and the faeces of children under the age of five were not left in the open. The socioeconomic and demographic characteristics that were used as covariates in multivariable analyses are women's age, education, occupation, religion, caste, exposure to mass media, place of cooking, place of delivery of child, birth order and the wealth status of the household. The wealth status of the household included a range of variables reflecting socioeconomic status of the household such as possession of various household and farming assets, type of house, type of cooking fuel, source of drinking water and possession of land. The detailed procedure of arriving at the wealth index is available elsewhere.[27] The covariates were recoded from the original questions to make them suitable for the analysis. Multivariable analyses were also adjusted for birth order of the index child and place of delivery.

Table 1 Profile of women who gave birth in the 5 years preceding the survey residing in urban areas for which ambient air pollution data was available, NationalFamily Health Survey-4, 2015/2016

	% or mean (SD)
Characteristics of women/ household	**n=19 000**
Age of women, mean (min–max, SD)	27.4 (15–49, 4.8)
% of women with formal education	88.4
% of women belonging to the Hindu religion	72.3
% of women belonging to scheduled caste/scheduled tribe	23.6
% of women belonging to poor household	15.1
% of women who have exposure to mass media	95.0
% who have a separate room for the kitchen inside the house	64.6
% practicing good hygiene	55.0
Birth order of the index child, mean (min–max, SD)*	1.8 (1–14, 1.1)
Annual PM_{10} level (μg/m^3), mean (min–max, SD)	101.0 (24.4–258.7, 52.5)

*Computed based on the birth data, n=23 954.
PM_{10}, particulate matters of size below 10 μg/m^3; SD, Standard Deviation
.

Statistical analysis

Univariate, bivariate and multivariable analyses were conducted using Stata 15.2. Univariate analysis was conducted to present the profiles of the women and characteristics of their households. Bivariate analyses were conducted to understand the unadjusted association between levels of PM_{10} and child health outcomes. Multivariable analyses were conducted to understand the socio-demographic, maternal and household characteristics adjusted effects of PM_{10} on child health outcomes. For bivariate and multivariable analyses, multilevel models were fitted where births were nested within PSUs which were nested within a district. For neonatal and post-neonatal mortality, survival regression with Weibull distribution was used to estimate the relative risk ratio of deaths. For premature births, children with ARI symptoms, and low birth weight, separate logistic regression models were fitted to estimate the effects of PM_{10}. The results from logistic regressions were presented in the form of ORs. Actual PM_{10} values were divided by 10 for use in the regression models. All the multivariable models were adjusted for women's age, education, mass media exposure, religion, caste, birth order of the index child, place of delivery, household's place of cooking and wealth status of the household. Generalised sensitivity analysis was conducted to test model assumptions. This analysis was done without using the survey weight as the statistical programmes available in Stata to perform sensitivity analysis do not support including survey weights. However, this should not influence on the sensitivity analyses results as the effect sizes of the unweighted and weighted sample remain almost same. The generalised sensitivity analysis was supplemented with Monte Carlo simulation to test the robustness of the estimates.[28 29]

Patient and public involvement

The study used data from a population-based household survey. Therefore, it did not directly involve the respondents in study planning. However, the International Institute for Population Sciences, the nodal institute responsible for collection of data, sought guidance for study planning and results dissemination from technical advisory committee formed by Ministry of Health and Family Welfare, which included community representatives and technical experts.

RESULTS

Profile of women in the analytical sample

Women in the analytical sample were, on average, 27 years old (SD: 5 years) (table 1). The majority (88%) of them were educated with some level of formal education, exposed to mass media (95%) and about one-quarter (24%) belonged to scheduled caste or scheduled tribe communities. Only 15% of the women were from poor households. Nearly two-thirds (65%) of the households used a separate room for the kitchen, and more than half (55%) followed good hygiene practices. The annual average PM_{10} for the 184 study districts was 101 µg/m^3.

Effect of PM_{10} on child health outcomes

For every 1000 live births, about 15 newborns died in the first week of their birth and another 7 died before their first birthday (table 2). A little less than one-fifth (17%) of children were born weighing less than 2500 g, whereas more than one-fifth (22%) of children experienced symptoms of ARI in the 2 weeks preceding the date of the survey. When analysed after controlling for sociodemographic factors and hygiene practices, reported levels of PM_{10} were found to have a significant effect on child health outcomes. For example, with every 10 µg/m^3 increase in PM_{10} level, the risk of neonatal mortality increased by 6%, the odds of experiencing ARI symptoms by 7% and premature births by 8%. Further, the hygiene practices followed by a household had an independent effect on all child health outcomes except for experiencing ARI symptoms. For example, the risk of neonatal deaths increased by more than four times if the child was born in a household with poor hygiene practices compared with those born in households with good hygiene practices (adjusted relative risk: 4.35, p<0.01).

Sensitivity analysis to check robustness

The sensitivity analysis based on Monte Carlo simulation suggests that the estimates from the original models were robust (online supplementary table S1). While the

Table 2 Association between exposure to outdoor air pollution and child health outcomes in urban areas

Health outcomes	Rate (N)	Model 1*: Effect with every 10 µg/m^3 increase in PM_{10} RR/OR (95% CI), p value†	Model 2*: Effect with every 10 µg/m^3 increase in PM_{10} Adjusted RR/OR (95% CI), p value†	Model 3*: Effect with every 10 µg/m^3 increase in PM_{10} Adjusted RR/OR (95% CI), p value†	Model 3*: Risk due to poor hygiene compared with good hygiene Adjusted RR/OR (95% CI), p value†
Neonatal deaths per 1000 live births	15.3 (23 954)	1.06 (1.03 to 1.10)	1.03 (1.00 to 1.07)	1.06 (1.02 to 1.09)	4.35 (3.45 to 5.47)
Post-neonatal deaths per 1000 live births	7.3 (23 954)	1.10 (1.05 to 1.15)	1.08 (1.03 to 1.13)	1.10 (1.05 to 1.16)	3.78 (2.66 to 5.39)
Children under age 5 with ARI symptoms per 1000 live births	21.6 (23 198)	1.06 (1.02 to 1.10)	1.07 (1.03 to 1.12)	1.07 (1.03 to 1.12)	1.01 (0.83 to 1.23)
Premature births per 1000 live births	72.2 (23 954)	1.07 (1.03 to 1.12)	1.07 (1.03 to 1.12)	1.08 (1.03 to 1.12)	1.28 (1.14 to 1.45)
Low birth weight per 100 live births	17.0 (20 993)	1.04 (1.02 to 1.05)	1.03 (1.01 to 1.04)	1.03 (1.02 to 1.05)	1.31 (1.21 to 1.42)

*Model 1 shows unadjusted effects whereas Model 2 and Model 3 are adjusted for women's age, education, mass media exposure, religion, caste, birth order of the index child, place of delivery, household's place of cooking and wealth status. Model 3 had hygiene as one of the added covariates.
†Relative risk (RR) and OR were estimated using multilevel mixed effects models with PM_{10} levels as a predictor. RR was estimated for neonatal and post-neonatal mortality and OR was estimated for symptoms of ARI, premature birth and low birth weight.
ARI, acute respiratory infection; PM_{10}, particulate matters of size below 10 µg/m^3.

Table 3 Association between exposure to outdoor air pollution and child health outcomes in urban areas by hygiene practice

Health outcomes	Effect with every 10 µg/m³ increase in PM_{10} among households with poor hygiene practices		Effect with every 10 µg/m³ increase in PM_{10} among households with good hygiene practices	
	Rate (N)	Adjusted RR/OR (95% CI), p value*	Rate (N)	Adjusted RR/OR (95% CI), p value*
Neonatal deaths per 1000 live births	23.3 (10 088)	1.08 (1.03 to 1.13)	8.4 (13 866)	1.03 (0.98 to 1.09)
Post-neonatal deaths per 1000 live births	10.5 (10 088)	1.10 (1.03 to 1.17)	4.5 (13 866)	1.11 (1.03 to 1.19)
Children under age 5 with ARI symptoms per 1000 live births	21.1 (9574)	1.04 (0.98 to 1.10)	22.1 (13 624)	1.09 (1.04 to 1.14)
Premature births per 1000 live births	68.2 (10 088)	1.06 (1.01 to 1.12)	75.7 (13 866)	1.10 (1.04 to 1.16)
Low birth-weight per 100 live births	18.5 (8651)	1.04 (1.01 to 1.06)	15.8 (12,342)	1.04 (1.02 to 1.06)

*Adjusted relative risk (RR) and adjusted OR estimated using multilevel mixed effects models. Covariates in the model included women's age, education, mass media exposure, religion, caste, birth order of the index child, place of delivery, household's place of cooking and wealth status. RR was estimated for neonatal and post-neonatal mortality, whereas OR was estimated for ARI, premature birth and low birth weight.
ARI, acute respiratory infection; PM_{10}, particulate matters of size below 10 µg/m³.

effect sizes remain same, the standard errors changed marginally. Sensitivity analysis undertaken to test the model assumptions suggest that the models were minimally sensitive to model assumptions and unmeasured observables (online supplementary figures S1–S5). For example, the sensitivity analysis for neonatal mortality suggests that if there exists a confounder as strong as SD of PM10 (sdymean_pm10), the estimated effect of PM10 on neonatal mortality will become half (online supplementary figure S1).

Effect of PM_{10} on child health outcomes by hygiene practices

Both neonatal (23 vs 8 deaths per 1000 live births) and post-neonatal (10 vs 4 deaths per 1000 live births) deaths were higher among households with poor hygiene conditions than those with good hygiene conditions (table 3). The stratified analysis by hygienic conditions of households showed that exposure to PM_{10} had a significant effect on almost all child health outcomes regardless of hygiene practices followed by a household. However, such effects were different between households with poor hygienic practices and good hygienic practices.

Effect of PM_{10} on child health outcomes by NCAP districts

The mean annual PM_{10} levels in NCAP cities were marginally higher than those in non-NCAP cities (table 4). While neonatal deaths and premature birth rates were marginally higher in NCAP cities than non-NCAP cities,

Table 4 Association between exposure to outdoor air pollution and child health outcomes in urban areas by NCAP city/town

Health outcomes	Effect with every 10 µg/m³ increase in PM_{10} among households in NCAP cities		Effect with every 10 µg/m³ increase in PM_{10} among households in non-NCAP cities	
	Rate (N)	Adjusted RR/OR (95% CI), p value*	Rate (N)	Adjusted RR/OR (95% CI), p value*
PM_{10} level, mean (min–max, SD)	118.6 (60.8 to 260.0, 43.4)		83.5 (24.4 to 261.0, 50.6)	
Neonatal deaths per 1000 live births	17.3 (14 185)	1.06 (1.02 to 1.11)	12.8 (9769)	1.04 (0.99 to 1.10)
Post-neonatal deaths per 1000 live births	7.3 (14 185)	1.13 (1.05 to 1.22)	7.3 (9769)	1.08 (1.02 to 1.16)
Children under age 5 with ARI symptoms per 1000 live births	22.0 (13 698)	1.10 (1.03 to 1.17)	21.2 (9500)	1.06 (1.00 to 1.13)
Premature births per 1000 live births	74.5 (14 185)	1.09 (1.01 to 1.16)	69.3 (9769)	1.10 (1.04 to 1.15)
Low birth weight per 100 live births	17.5 (11 942)	1.01 (0.99 to 1.04)	16.5 (9051)	1.04 (1.01 to 1.06)

*Adjusted relative risk (RR) and adjusted OR estimated using multilevel mixed effects models. Covariates in the model included women's age, education, mass media exposure, religion, caste, birth order of the index child, place of delivery, household's place of cooking and wealth status. RR was estimated for neonatal and post-neonatal mortality, whereas OR was estimated for ARI, premature birth and low birth weight.
ARI, acute respiratory infection; NCAP, National Clean Air Program; PM_{10}, particulate matters of size below 10 µg/m³.

those differences were not statistically significant. The stratified analysis by NCAP district revealed that exposure to PM_{10} had a significant effect on almost all child health outcomes regardless of whether or not the child was born in an NCAP city. For example, premature births were likely to increase by 9 to 10 times with every 10-unit increase in PM_{10} values in NCAP and non-NCAP cities.

DISCUSSION

The effects of air pollution on children are devastating given they breathe faster than adults, and inhale more polluted air because they live closer to the ground where the concentration of some pollutants is very high.[30–33] This was reconfirmed by the current study based on data from 184 towns and cities in India which showed that exposure to PM_{10} not only affects children but also pregnant women resulting in premature births. The strength of this study lies in the fact that it was based on analysis of PM_{10} levels from 184 towns and cities, unlike prior studies that were mostly focussed on metro cities. The study also noted that the effect of PM_{10} on child health outcomes did not vary between NCAP and non-NCAP cities. This suggests that the effects of air pollution were not limited to metro cities rather the effects were felt across India. Therefore, it is suggested that the efforts of NCAP should go beyond the 102 towns identified for intervention. Unless appropriate mechanisms to improve ambient air quality are put in place, air pollution will continue to pose serious public health concerns in the coming years. The study found the average PM_{10} level to be 101 µg/m^3 per year across the studied urban areas. Empirical studies have shown that levels of $PM_{2.5}$, the more harmful pollutant, are likely to be much higher than the PM_{10} levels. Therefore, effective public health strategies need to be developed to deal with air pollution.

Earlier studies examining the effects of PM_{10} on child health outcomes such as mortality, adverse pregnancy outcomes (premature birth and low birth weight) and ARI have documented the various pathways through which PM_{10} affects children before birth leading to premature death. The effect starts with premature birth and low birth weight, which then heightens the risk of mortality of a child at a later stage.[34–36] Empirical studies have documented that exposure of pregnant women to PM_{10} affects several haematological indicators such as haemoglobin level, platelets, white blood cells and blood coagulation capacity which leads to adverse fetal growth.[37 38] These lead to both premature birth and low birth weight. Children with low birth weights are more likely to develop infections during early childhood, which may cause developmental delays including neurological development,[30 35 36 39] ARI[38 40] and possibly malnutrition.

In line with prior research,[41–44] this study found that the risk of mortality (both neonatal and post-neonatal) was much higher for children living in unhygienic conditions than those in hygienic conditions. Moreover, exposure to PM_{10} in addition to poor hygienic living conditions would only enhance the risk of death. Interestingly, air pollution had no differential effect on children's health regardless of whether they lived in hygienic or unhygienic conditions, except for the symptoms of ARI. The exposure to PM_{10} had a significant effect on ARI symptoms among children living in good hygienic conditions, whereas no such association was noted for children staying in unhygienic conditions. Intriguingly, PM_{10} had a significant effect under good hygienic conditions. This could have been because of the manner in which the presence of ARI symptoms among children was measured in this study. Whether children were experiencing symptoms of ARI or not was computed based on symptoms reported by the mothers. Post-hoc analysis suggests that more than 90% of women from households following hygienic practices were rich and educated, which may have helped them to more accurately recognise and report symptoms of ARI than women from households with bad hygienic practices. Beside this, the effects of genetic conditions or lifestyle should not be ruled out. The study also found that the magnitude of the effect of hygienic practices on child health was far greater than the effect of PM_{10}. This could be a statistical fallacy due to the varying nature of measurement scales used to assess the effect. While air pollution was measured on a continuous scale, the variable that represented hygienic practice was dichotomous. Statistical effects, particularly in non-linear regression are more visible in magnitude for categorical explanatory variables than for continuous variables.[45]

While the study findings have provided insights into the effects of PM_{10} on child health, they should be interpreted with some caution. First, the data used were cross-sectional and the effects shown may not be indicative of true causation. Given that some of the earlier epidemiological studies have already shown the causal effect of PMs on child health, these findings hold true. Moreover, this study found that there are limited number of studies that have adopted a life-course approach to understand these relationships epidemiologically. Therefore, epidemiological research based on a life-course approach should be taken up to understand the pathways through which air pollution affects children. Second, as per the box model the exposure to PM_{10} within a district was assumed to be uniform for all women and children. However, there may be a varying degree of exposure due to spatial variation and hence a differential effect on health outcomes. However, it is still useful for general estimations of average pollution levels. This is an area where India has limited information, and future research on air pollution should focus on collecting data from more geographical points on pollutants' concentration level to adjust for spatial variances, the degree of exposure to various pollutants or test measurement approaches on the degree of exposure. Third, this study excluded a large share of births from the overall sample for which data were collected due to unavailability of PM_{10} data. Therefore, the results presented only refer to a cross-section of data collected from a limited urban area of India. Nevertheless, given the large sample size, the findings presented in the study still hold and represent the 184 cities/towns considered in the study. The lack of data on ambient air pollution levels in rural areas is a key gap in India's efforts to address air pollution, and therefore efforts must be made to measure air pollution in rural areas, at least in the rural areas located on the peripheries of urban areas. Fourth, the child health outcome indicator on ARI was reported by the mother of the child and hence there may be certain errors in the reporting of this indicator. Similarly, the data on birth weight was taken from medical cards wherever available, and otherwise reported by the mother. Hence, there will be certain reporting errors in this indicator too. To minimise reporting bias in these indicators, particularly for experiencing the symptoms of ARI, the NFHS used validated questions to help respondents respond to various symptoms without any ambiguity. Fifth, this study examined the effects of $PM_{10;}$ however, there are other pollutants such as $PM_{2.5}$ as well as household air pollution that may have contributed to the negative child health outcomes. We suggest that future research explores how household air pollution interacts with ambient air pollution and how they individually and jointly affect health outcomes. Sixth, there may be other comorbidities or health conditions that may have led to the death of children that this study did not explore. Lastly, for this analyses, we assumed the shape of the concentration-response function between air pollution exposure and health effects to be linear. While we are aware of the application of statistical models to analyse this relationship, there is limited existing information of such functions at high average chronic exposure levels such as we report in our analyses (average annual PM_{10} 101.0 $\mu g/m^3$), for the outcomes reported in our analyses.[46 47]

The ever-increasing rate of urbanisation and industrialisation means that air pollution levels are expected to increase in the coming years if the status quo is maintained. To mitigate the effects of air pollution, there needs to be a structural as well as behavioural change. The NCAP is a good start; however, its efforts should be extended to towns that are not part of NCAP. In addition, policies that discourage the use of biofuel need to be implemented across the country with more rigour, supported by effective monitoring of such implementation. Further, use of solar energy should be promoted across all cities and towns. Currently, a few state governments offer subsidies to promote the use of solar energy. However, awareness about solar energy and its benefit is limited among the general population. Along with the subsidy, there needs to be marketing that helps people understand the benefits of solar energy. In addition to these system-level efforts, there needs to be an investment to change the behaviour of individuals. For example, air pollution in most north Indian towns during winter is a result of stubble burning in addition to industrial pollution. While there have been efforts and laws to prevent stubble burning, this has not led to any change in the situation on the ground. Interventions that can change the attitude and behaviours of farmers engaging in stubble burning may help in reducing these emissions. Similarly, use of vehicles and auto-rickshaws running on fossil fuels are on the increase across Indian cities and towns. There need to be efforts that increase awareness about vehicular emission and the promotion of regular pollution checks and proper maintenance of vehicles, which can reduce the emission of harmful pollutants. Finally, current research on air pollution in India is restricted to only a few cities and this needs to be expanded to other towns to examine what the major pollutants are and their sources. This can help in developing more localised town-specific plans for mitigating the ill effects of air pollution. In conclusion, the study using PM_{10} data for 184 cities found that exposure to PM_{10} affects the health of children regardless of hygienic conditions and socioeconomic status. While this study focussed on studying the effects of PM_{10}, future studies should also examine how PM_{10} affects non-communicable diseases including mental health. In addition, data on household air pollution are scarce in India and efforts should be put in place to generate robust data on household air pollution that can help researchers and policymakers understand the interaction of ambient and household air pollution and their effect on human health, specifically, the health of mother and children.

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