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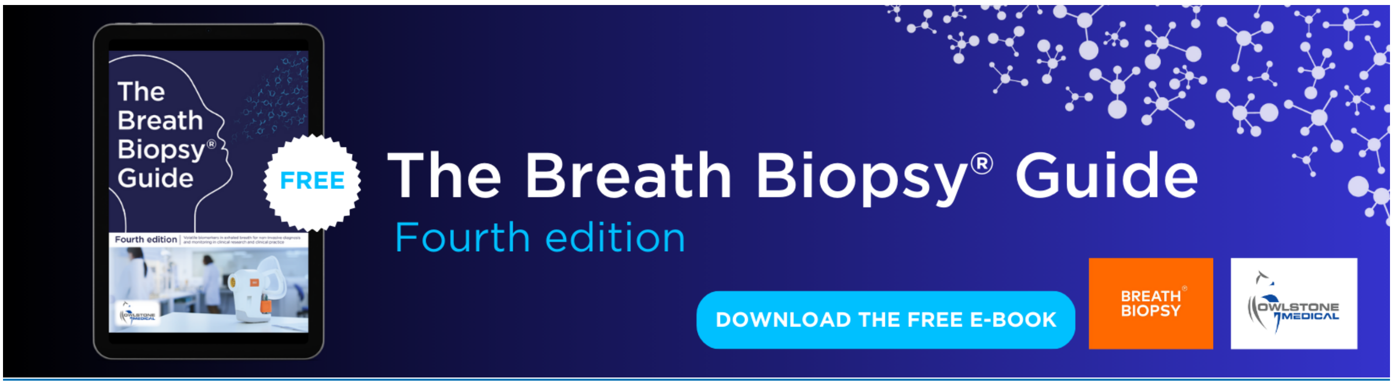

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LETTER

High ambient air pollution erodes the benefits of using clean cooking fuel in preventing low birth weight in India

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Abstract

A large fraction of the population in rural India continues to use biomass fuel for cooking and heating. In-utero exposure to the resulting household air pollution (HAP), is known to increase the risk of low birth weight (LBW). Mitigating HAP, by shifting to clean cooking fuel (CCF), is expected to minimize the risk associated with LBW. However, India also has high levels of ambient air pollution (AAP). Whether exposure to AAP modifies the effect of reducing HAP by switching to CCF on LBW is not known. The present study addressed this knowledge gap by analyzing the National Family Health Survey (2019–21) data of the most recent full-term, singleton, live births from rural households born after 2017 ($n = 56\,000$). In-utero exposure to AAP was calculated from satellite-derived ambient fine particulate matter ($PM_{2.5}$) concentration at the level of the primary sampling unit for the pregnancy duration of the mothers. The moderation by ambient $PM_{2.5}$ level on the odds of LBW among CCF users was examined by logistic regression analysis with interaction. The adjusted odds ratio (aOR) of LBW was 7% lower among users of CCF. At the lowest Decile (20–37 μg m^{-3}) of ambient $PM_{2.5}$ exposure, the aOR of LBW among CCF users was 0.83 (95% CI:0.81–0.85). At every 10th percentile increase in ambient $PM_{2.5}$ exposure (in the range 21–144 μg m^{-3}), aOR increased gradually, reaching the value of 1 at $PM_{2.5}$ level of 93 μg m^{-3}. Our results, therefore, suggest that the benefit of using CCF during pregnancy may be downgraded by moderate to high ambient $PM_{2.5}$ exposure.

1. Introduction

India faces a high burden of air pollution-related mortality and morbidity. In 2019, there were an estimated 0 · 61 million deaths and 20·9 disability-adjusted life years (DALYs) attributable to household air pollution (HAP) in India. These accounted for 6.5% of the total deaths and 4·5% of total DALYs in the country [1]. HAP is mainly a rural problem, with almost 57% of rural households relying on biomass solid fuel (such as wood, crop residue, dung cakes, and charcoal) for cooking food and water and space heating [2]. Previous research has established a causal association between HAP and adverse birth outcomes [3], childhood morbidity, and mortality [4–6]. A range of HAP-related adverse birth outcomes have been reported in the literature, such as having a low birth weight (LBW) baby, pre-term birth, and stillbirth [7–11].

Biomass fuel burning results in high levels of particulate matter ($PM_{2.5}$) and gaseous air pollutants such as carbon particles, iron, lead, cadmium, silica, phenols and free radicals, carbon monoxide (CO), nitrogen dioxide, sulfur dioxide, formaldehyde, hydrocarbon complexes, and other inorganic and organic substances which include polycyclic aromatic hydrocarbons, volatile organic compounds, and chlorinated dioxins [12]. Fine $PM_{2.5}$ (of size less than 2.5 μm in aerodynamic diameter) and CO, two important by-products of incomplete combustion, are absorbed in the maternal blood, cross the placental barrier, and impair fetal tissue growth through hypoxia/oxidative stress [3]. A higher risk of LBW is observed with the use of biomass and coal for cooking during pregnancy, compared to clean fuel (gas and biogas) [13]. LBWs were documented in households that cooked with unclean fuels in houses with or without separate kitchens or outdoors, compared to those using clean fuels [14].

More recent evidence from studies that rely on direct exposure measurement further adds to the evidence [15]. In a study by Balakrishnan *et al*, the odds of LBW were found to increase by 2% with a 10 μg m^{-3} increase in $PM_{2.5}$ emitted from solid fuel use in households. A non-linear relationship between $PM_{2.5}$ and birth weight (initial increase in birthweight with higher $PM_{2.5}$ followed by a subsequent decrease at the higher exposures) was observed in a multi-country randomized clinical trial [16]. Although limited, more recent evidence also raises the possibility of the influence of ambient air pollution (AAP) on the LBW-HAP risk association [17]. Existing research from India reports a negative association between ambient $PM_{2.5}$ exposure and child health outcomes such as birth weight [18] and infant mortality [19]. However, the interacting effect of HAP and AAP on child health remains less explored in India.

India has seen a rapid growth of domestic use of clean cooking fuel (CCF) across the country in the last decade. The *Pradhan Mantri Ujjwala Yojana* (PMUY) [20], was launched in 2016 to facilitate this transition and reduce the disease burden associated with HAP [1]. However, there is a sizeable inter-state variation in the use of CCF. Rural parts of northern and eastern parts of India still have low proportions of primary users of CCF [21]. The same region, almost the entire Indo-Gangetic plain, also has high ambient $PM_{2.5}$ levels [19]. It is important to understand how the dual burden of AAP and HAP influences the health benefits of CCF intervention [22].

With this view, we analyzed the national family health survey (2019–21, NFHS-5) data to assess the effectiveness of transition to CCF in reducing the risk of LBW in the presence of varying levels of AAP.

2. Material and methods

2.1. Health data

The NFHS-5 is a nationwide survey conducted under the aegis of the Ministry of Health and Family Welfare, Government of India [21]. It adopts a uniform, multi-stage random sample design to have a representative sample at the national, state/union territory, and district levels. Each district is stratified into urban and rural areas. Within each explicit rural sampling stratum, a sample of villages is selected as Primary Sampling Units (PSUs) (also referred to as clusters). A total of, 30,456 PSUs were selected across the country in NFHS-5 drawn from 707 districts. At the household level, information was collected on socioeconomic characteristics and various social determinants of health. The Woman's Questionnaire collected information from all eligible women aged 15–49, on many topics, including children born and birth details. Relevant information from household and woman's questionnaires was used for the present study.

The primary outcome—birth weight was based on reporting by the mother. The information was recorded from a health card in 63.8% of cases and from the mother's recall in the remaining. LBW babies were defined as babies weighing below 2500 g at birth (categorical variable). Our analysis included the most recent full-term, singleton live births from rural households born after 2017. The total sample size in the NHFS-5 was 95374, out of which 39374 cases could not be included in the analysis due to multiple factors (figure 1) and the final sample size included in our analysis for whom information on exposure to HAP and AAP was available was 56000.

2.2. Exposure data

2.2.1. HAP

The type of cooking fuel reported by each woman was used to assign HAP exposure status to each case. Women who reported the primary use of solid cooking fuels (SCF) (coal, lignite, charcoal, wood, straw/shrubs/grass, agricultural crop, animal dung) were classified as 'exposed' or 'SCF users'. Those reporting primary use of liquefied petroleum gas (LPG), electricity, natural gas, and biogas were classified as 'unexposed' or CCF users. Figure 2(a) provides proportion of women using solid fuels for cooking, by primary sampling unit in the rural area.

2.2.2. AAP

AAP was assigned in terms of average ambient $PM_{2.5}$ exposure during pregnancy derived for each PSU. Due to inadequate coverage of India's ground monitoring network, particularly in rural areas, we used a satellite-derived $PM_{2.5}$ dataset from a published study Katoch *et al* [23]. This dataset was generated by converting daily aerosol optical depth (AOD) at 1 km^2 resolution, retrieved from the Moderate Resolution Imaging Spectroradiometer into surface $PM_{2.5}$ concentrations. To address missing data in the daily AOD due to retrieval challenges and cloud cover, the XGBoost machine learning technique was employed. This technique utilized various predictor variables including temperature, cloud fraction, relative humidity, albedo, boundary layer height, zonal and meridional wind, and total columnar water. Subsequently, the gap-filled AOD data was employed in the Random Forest Machine Learning Technique to predict daily $PM_{2.5}$ at the same 1 km^2 resolution. In addition to the predictor variables utilized for AOD gap-filling, supplementary variables such as the nearest fire incident distance from the

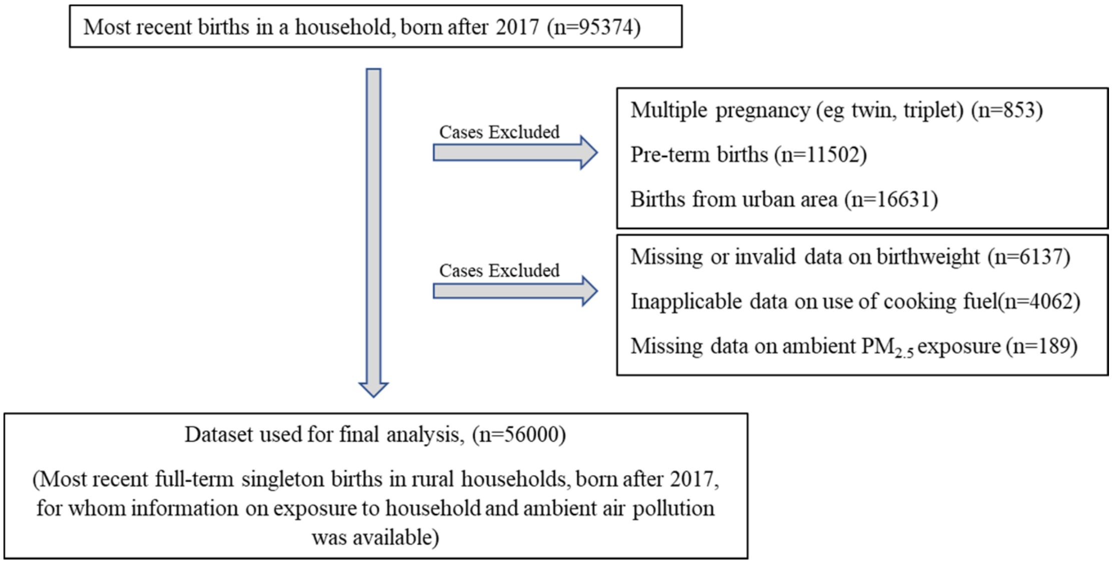

Figure 1. The consort diagram describes the inclusion and exclusion process of selecting a final analytical sample from the National Family Health Survey-5.

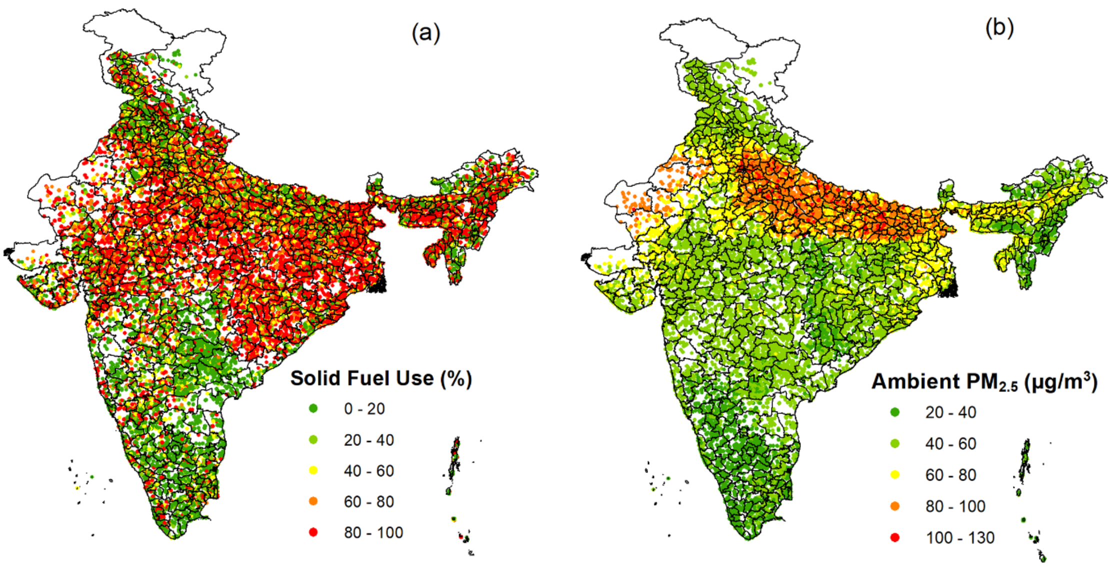

Figure 2. Spatial patterns of ambient and household air pollution exposure among study population. (a) Proportions of women primarily using solid fuel for cooking, by rural PSUs (b) average ambient $PM_{2.5}$ exposure during intrauterine period, by rural PSUs.

measured location, distance to major and minor roads, elevation, land use variables, and population density were also used in this model. The performance of the dataset was evaluated against coincident measurements from the Central Pollution Control Board (CPCB) ground monitoring network, which comprised of continuous ambient air quality monitoring stations (CAAQMS) and manual monitors. CAAQMS measures and reports $PM_{2.5}$ every 15 min across 144 cities spanning 24 states and union territories. The real-time data is disseminated through the CPCB portal (https://app.cpcbccr.com/ccr/#/caaqm-dashboard-all/caaqm-landing) in real-time. In contrast, manual monitoring occurs twice a week for a 24-hour cycle, resulting in a maximum of 104 measurement days per year at the respective sites. During the time period considered in this study, the surface $PM_{2.5}$ reported an R^2 of 0.85 and RMSE of 23.3 μg m^{-3} on a daily scale against measurements from the reference-grade monitors maintained by the CPCB (appendix A). More details on the distribution of CPCB ground-based monitors are given in Katoch *et al* [23].

2.3. Exposure attribution

NFHS-5 survey provided geolocations for each PSU within the 2 km (urban) and 5 km (rural) buffer surrounding the cluster location. We assigned daily ambient $PM_{2.5}$ levels within the urban and rural buffers across the PSUs and extracted intrauterine exposure (for 9 months through birth), based on the month of delivery and pregnancy duration information available in NFHS-5, for every woman-child pair (ranging from 21 to 144 $\mu g\ m^{-3}$). Figure 2(b) provides the spatial pattern of intrauterine ambient $PM_{2.5}$ exposure among women included in the analysis at the PSU levels. Using percentile-based classification (every 10th percentile), ten Deciles (I to X) depicting low to high levels of ambient $PM_{2.5}$ exposure were identified (Decile I ranging from 20–37 $\mu g\ m^{-3}$, Decile II from 37–42 $\mu g\ m^{-3}$, Decile III from 42–46 $\mu g\ m^{-3}$, Decile IV from 46–51 $\mu g\ m^{-3}$, Decile V from 51–55 $\mu g\ m^{-3}$, Decile VI from 55–62 $\mu g\ m^{-3}$, Decile VII from 62–70 $\mu g\ m^{-3}$, Decile VIII from 70–79 $\mu g\ m^{-3}$, Decile IX from 79–93 $\mu g\ m^{-3}$, Decile X from 93–144 $\mu g\ m^{-3}$).

2.4. Covariates

The following covariates were considered while calculating the risk of LBW—household level factors (the location where food is cooked, wealth index, social grouping), maternal level factors (age, education, received antenatal care, pregnancy intention, presence of anemia, body mass index), and baby level factors (birth order, gender of the baby). The information about covariates was obtained from the NFHS-5 questionnaires.

Socioeconomic status was quantified using two variables—individual wealth index (with levels of 'poorest', 'poorer', 'middle', 'richer' and 'richest.') and social group (with levels 'Scheduled Caste' (SC), 'Scheduled Tribe'(ST), 'Other Backward Class' (OBC) and 'none of these'). SC, ST, and OBCs are formally recognized categories in India representing communities facing significant socio-economic disadvantages. The location where food is cooked was categorized as 'Outdoor /separate building' and 'Indoor'. Two age categories were used—<20 years and 20 years or more. Information about levels of education was categorized as 'primary', 'secondary', 'higher', and 'no education'. The intention to have the pregnancy was categorized as 'wanted pregnancy then', 'wanted pregnancy later', or 'did not want pregnancy'. In NFHS-5, the eligible age group for height, weight, and hemoglobin measurements among women was 15–49 years. Hemoglobin analysis was conducted onsite with a battery-operated portable HemoCue Hb 201+ analyzer. Anemia was categorized as severe anemia (<7.0 g dl^{-1}), moderate anemia (7.0–9.9 g dl^{-1}), mild anemia (10.0–10.9 g dl^{-1} for pregnant women and 10.0–11.9 g dl^{-1} for other adult women). Body mass index (BMI) was categorized as underweight (BMI $<$ 18.5), normal (BMI 18.5–24.9), overweight (BMI 25.0–29.9), and obese (BMI $\geqslant$ 30.0).

Smoking, which may directly affect the level of in-utero exposure, was not included as <1% of women had a history of smoking.

2.5. Statistical model

Logistic regression analysis was undertaken to calculate the odds of having LBW among CCF users compared to SCF users. Univariate and multivariate analyses were undertaken, applying individual-level weights. Multivariate analysis included covariates reported in previously published studies [24] and for which data were available from an adequate number of respondents in the NFHS-5. Stratified analysis (by PSU level average ambient $PM_{2.5}$ level during the intrauterine period) was undertaken using an interaction model to assess the effect modification of HAP-LBW association by ambient $PM_{2.5}$ levels. Statistical analyses were done using R version 4.2.2 (R Core Team, 2023, Vienna, Austria).

We also evaluated whether the outcome assessment method changed the observed effects, by undertaking sensitivity analysis. In NFHS-5, the information on birth weight was obtained from the health card or based on the mother's recall. In 35693 (63.74%) cases, information on birth weight was obtained from the health card, and in 20307 (36.26%) cases information was based on the mother's recall. A separate analysis was undertaken for both these cohorts. Sensitivity analysis was also undertaken by excluding cases with birth weight exceeding 4000 gm.

3. Results

3.1. Risk of LBW by type of cooking fuel

Of the 56,000 mother-infant pairs, only 35.2% of women reported primary use of CCF. LPG was the most commonly used CCF. Women reporting primary use of CCF were more educated, had a higher wealth index, and had a lower level of anemia and undernourishment (table 1). The overall proportion of LBW was 17.8% (95% CI: 17.3–18). The weighted proportion of LBW was lower among users of CCF [15.6%, (95% CI: 14.7–16.5)] compared to SCF [19.1%, (CI: 18.6–19.7)]. The median birth weight was 2.8 kg. It was lower among users of SCF [2.75 kg, (95% CI: 2.72–2.77)], compared to CCF [2.9 kg, (95% CI: 2.85–2.94)].

Multivariate logistic regression analysis (entire cohort) showed that the odds of LBW were 7% lower among users of CCFs compared to SCFs (adjusted odds ratio, aOR = 0.93, 95% CI: 0.87–0.98, $p = 0.01$). In other words, a statistically significant protective effect was observed among primary users of CCF at the country level.

Table 1. Characteristics of the study population and prevalence of LBW.

		Total cases	Low birth weight babies	
		N	n	P (95% CI)[a]
Type of cooking fuel				
	Clean fuel	19 736	2847	15.61 (14.72–16.5)
	Solid fuel	36 264	6482	19.11 (18.57–19.66)
	Total	56 000	9329	
Location where food is cooked				
	Outdoor /separate building	14 125	2469	18.63 (17.77–19.48)
	Indoor	41 875	6860	17.5 (16.93–18.07)
	Total	56 000	9329	
Wealth index				
	Poorest	12 222	2364	20.56 (19.6–21.53)
	Poorer	11 640	2094	19.71 (18.73–20.69)
	Middle	10 872	1858	18.43 (17.47–19.4)
	Richer	10 302	1522	15.82 (14.9–16.74)
	Richest	10 964	1491	14.42 (13.05–15.79)
	Total	56 000	9329	
Social group				
	Scheduled Caste	11 632	2181	19.14 (18.12–20.17)
	Scheduled Tribe	12 819	1975	19.32 (17.98–20.66)
	Other Backward Class	21 473	3569	16.95 (16.32–17.58)
	None of these	7606	1235	16.84 (15.71–17.96)
	Do not know	273	54	21.77 (15.36–28.18)
	Total	53 803	9014	
Mother's age				
	⩾20 yrs	53 425	8804	17.53 (17.03–18.02)
	<20 yrs	2575	525	22.21 (20–24.41)
	Total	56 000	9329	
Education				
	No education	11 618	2315	20.96 (20.01–21.9)
	Primary	6945	1299	20.01 (18.75–21.28)
	Secondary	30 433	4869	17.41 (16.79–18.03)
	Higher	7004	846	12.7 (11.45–13.96)
	Total	56 000	9329	
Body Mass Index				
	Undernourished	11 803	2459	21.75 (20.78–22.72)
	Normal	35 301	5649	17.07 (16.51–17.64)
	Overweight	6123	810	14.56 (13.37–15.76)
	Obese	1436	172	13.15 (10.9–15.4)
	Total	54 663	9090	
Anemia				
	Severe anemia	1219	253	22.8 (19.75–25.86)
	Moderate anemia	17 335	3007	18.12 (17.35–18.89)
	Mild anemia	14 606	2452	17.68 (16.85–18.52)
	No anemia	20 985	3297	17.23 (16.48–17.98)
	Total	54 145	9009	
Antenatal care				
	Not received AN care	2463	483	21.27 (19.18–23.37)
	Received AN care	53 537	8846	17.61 (17.12–18.11)
	Total	56 000	9329	
Pregnancy intention				
	Wanted pregnancy then	52 135	8633	17.68 (17.17–18.18)
	Wanted pregnancy later	2245	382	17.94 (15.88–20)
	Did not want pregnancy	1620	314	20.61 (18.13–23.09)
	Total	56 000	9329	

(Continued.)

Table 1. (Continued.)

		Total cases	Low birth weight babies	
		N	n	P (95% CI)[a]
Birth order				
	First birth	20 962	3697	18.75 (18.03–19.46)
	Second birth	18 550	2951	16.94 (16.19–17.7)
	Third birth	9108	1468	17 (15.77–18.23)
	4 or more	7380	1213	18.11 (16.97–19.24)
	Total	56 000	9329	
Gender of the baby				
	Male	29 186	4508	16.48 (15.78–17.18)
	Female	26 814	4821	19.18 (18.55–19.81)
	Total	56 000	9329	
Ambient PM2.5 level				
	Decile I (20, 37)	5600	744	14.73 (13.36–16.09)
	Decile II (37, 42)	5600	849	16.59 (15.19–17.99)
	Decile III (42, 46)	5600	830	16.06 (14.7–17.42)
	Decile IV (46, 51)	5600	860	16.54 (15.15–17.93)
	Decile V (51, 55)	5600	933	19.02 (16.07–21.96)
	Decile VI (55, 62)	5600	990	18.44 (17.12–19.77)
	Decile VII (62, 70)	5600	1015	18.62 (17.31–19.92)
	Decile VIII (70, 79)	5600	1006	18.03 (16.79–19.27)
	Decile IX (79, 93)	5600	1023	18.94 (17.7–20.17)
	Decile X (93, 144)	5600	1079	18.86 (17.64–20.08)
	Total	56 000	9329	

[a] Prevalence (with 95% confidence interval) of LBW babies calculated after applying sampling weights.

3.2. Effect modification by ambient $PM_{2.5}$ exposure

The stratified analysis by categories/levels of ambient $PM_{2.5}$ exposure shows a heterogeneous picture (figure 3). In the lowest Decile of ambient $PM_{2.5}$ exposure (below 37 μg m^{-3}), the aOR of having an LBW baby with CCF use was 0.83 (95% CI:0.81–0.85). A gradient between aOR and ambient $PM_{2.5}$ exposure was observed. For the second, third, and fourth Deciles of ambient $PM_{2.5}$ exposure, the aORs did not change much. Afterwards, for every 10th percentile increase in ambient $PM_{2.5}$ exposure, the aOR increased gradually reaching the value of 1 for the ninth Decile. When in-utero ambient $PM_{2.5}$ exposure exceeded 93 μg m^{-3}, the aOR exceeded 1 indicating that the benefit of switching to CCF was outweighed by the negative effect of AAP.

3.3. Sensitivity analysis—

The sensitivity analysis, by outcome measurement method, showed the same trends as seen in the main analysis. For every 10th percentile increase in ambient $PM_{2.5}$ exposure, the aOR increased gradually. (More details in appendix B) Sensitivity analysis undertaken after excluding cases with birth weight exceeding 4000 gm, showed trends similar to that seen in the main analysis. (More details in appendix C)

4. Discussion

Our national-level analysis shows a reduced risk of LBW among CCF users. However, the stratified analysis (by levels of ambient $PM_{2.5}$ exposure) shows that AAP acts as an effect modifier of the risk association between LBW and the type of cooking fuel. The protective effect of CCF declined with increasing levels of ambient $PM_{2.5}$ levels.

There is limited evidence on the combined influence of HAP and AAP on birth weight in India. In a prospective cohort study from Beijing, China [17], the researchers explored the joint impact of indoor air pollution index and ambient $PM_{2.5}$ on fetal growth parameters (measured as abdominal circumference, head circumference, femur length, and estimated fetal weight). The risk ratios of foetal undergrowth were higher with exposure to 'higher ambient $PM_{2.5}$ and indoor air pollution' and 'higher ambient $PM_{2.5}$ and no indoor air pollution'; compared to lower levels of both. Our study results are in line with these findings. At the lowest level of ambient $PM_{2.5}$, the protective efficacy of CCFs was observed to be highest (aOR = 0.86). As the in-utero exposure to ambient $PM_{2.5}$ increased gradually from Decile I to X, the odds of LBW neared the value 1 (indicative of lesser efficacy of using CCFs for health benefits). It must be noted that the lowest Decile of $PM_{2.5}$ level observed in this study is higher than the air quality guideline set by the World Health Organization [25].

Previous studies across the globe have documented a negative association between ambient $PM_{2.5}$ levels and birth weight [26]. The heightened risk of LBW due to AAP is likely to have negated the advantage of the use of CCF. The possibility of fuel stacking (simultaneous use of clean and SCFs is considered as fuel stacking) also needs to be considered while

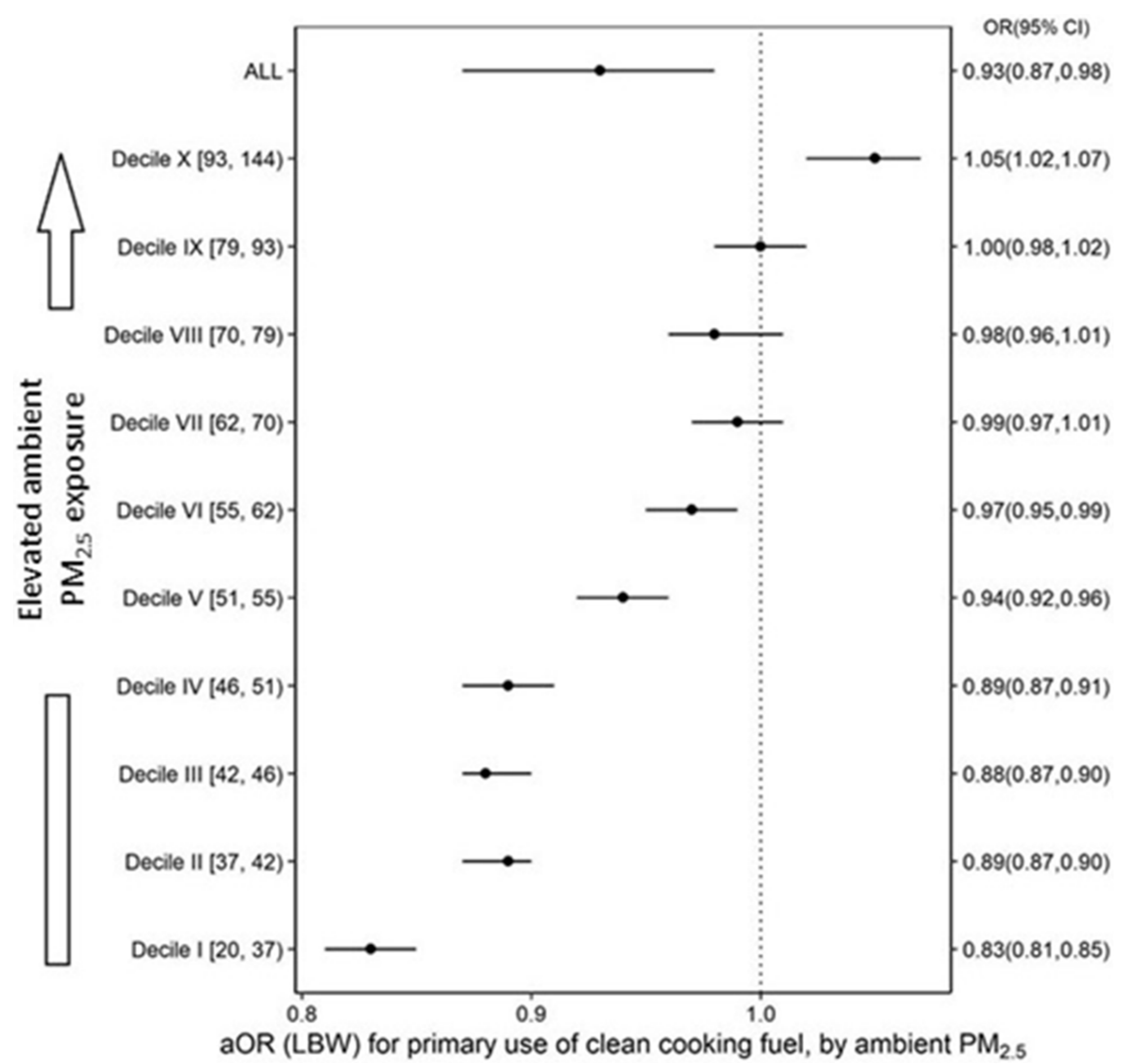

Figure 3. Odds of having LBW in women reporting primary use of clean cooking fuel, by ambient $PM_{2.5}$ level. (aOR—adjusted odds ratio; LBW—low birth weight, ambient $PM_{2.5}$ level is measured in μg m^{-3}. Reference category for logistic regression—women reporting primary use of solid cooking fuels).

interpreting the findings. The high and moderate AAP clusters in our analysis belong to energy-poor states in India [27]. In these areas, the transition to CCFs has been a relatively recent phenomenon, and many households still rely primarily on SCFs. It is known that transitioning away from traditional cooking fuels is a gradual process [27]. Therefore, even among primary users of CCF, a high level of stacking is likely [28] and can erode the health benefits [29]. Further investigations are needed to understand how personal exposures and associated health outcomes are affected based on the level of stacking in a household. The information gaps on stacking need urgent attention. The indicator on the primary use of cooking fuel used in existing surveys needs to be complemented with indicators that reflect the stacking level.

As seen in our analysis, there was a clear north–south divide in the level of air pollution. The use of SCFs is more prevalent in northern regions of the country, especially along the Indo-Gangetic plain. These regions also have higher ambient $PM_{2.5}$ levels. The average ambient $PM_{2.5}$ concentration during 2017–2021 in most of the rural PSUs from the Indo-Gangetic plain was above 50 μg m^{-3}. HAP significantly contributes (as high as 30%) to AAP in these regions [30]. Universal, complete, and sustained transition to CCF in these areas will not only help in eliminating HAP but will also result in a substantial reduction in AAP levels, rendering additional health benefits. Switching to clean fuel for domestic usage during pregnancy reduces household exposure and thereby lowers the risk of having an LBW baby. Such action will also reduce ambient PM2.5 exposure in varying margins depending on the relative contributions of household emissions across the states and will further lower the LBW risk. Further research is necessary to quantify these benefits.

The present study has a few limitations. It is based on a cross-sectional survey that collects data on current practices of cooking fuels and we assumed that the cooking fuel use was same during the period when the mother was pregnant. Since cooking behaviors are slow to change [27], it is more likely a valid assumption. The study lacks quantitative data on indoor $PM_{2.5}$ levels and instead uses proxy measures in the form of reported use of cooking fuel. Households primarily relying on solid fuels for cooking have high levels of $PM_{2.5}$ [31]. A study from India [32] modeled household concentrations of $PM_{2.5}$ as a function of multiple, independent household level variables available in national household surveys. The measured mean 24-hour concentration of $PM_{2.5}$ in SCF using households ranged from 163 μg m^{-3} in the living area to 609 μg m^{-3} in the kitchen area. Comparatively, the $PM_{2.5}$ levels are much lower among households with primary use of LPG. A multi-country randomized controlled trial [33] observed substantial exposure reductions in median kitchen $PM_{2.5}$ concentrations from 296 to 24 μg m^{-3} when households switched from solid to CCFs in rural settings. In NFHS-5, the information on birth weight was obtained from the health card (in most cases) or based on the mother's recall. This can induce recall bias for outcome measurement. However, sensitivity analysis by outcome measurement method (appendix B) did not show any difference in the risk analysis. Although the analysis was controlled for many known confounders, every possible confounder (e.g. obstetric history, maternal co-morbidity, work address, mobility during pregnancy etc.) could not be incorporated due to the lack of data.

While interpreting the findings of our analysis, it is also important to consider the deviations that occurred during NFHS-5 data collection due to the pandemic [21]. Phase 1 (22 states) of NFHS-5 lasted from July to December 2019. Phase 2 (14 states) started in January 2020, was halted from March to November 2020, and was finally completed in April 2021. Three free LPG cylinders were distributed to PMUY households during the financial year 2020–21. The average annual use of LPG cylinders in these households increased to 4.4 during 2020–21, compared to 2.8 in the previous year [34]. Even with this increase, many of the PMUY households are likely to have relied primarily on solid fuels, as 7–8 cylinders year^{-1} are typically required for a household of four people to completely shift to LPG-based cooking. Therefore, a sudden change in the category (from primary users of SCFs to primary users of CCFs) seems less likely during this time period. On the other hand, the level of stacking may have increased in non-PMUY households during the pandemic period due to access and affordability issues. This can erode the benefits of CFU. However, only a small proportion of the sample belongs to the abovementioned period. Around 15% of the births included in the analysis occurred during April—December 2020, and 2% occurred in 2021.

Finally, AAP exposure during pregnancy was estimated using satellite-$PM_{2.5}$ and it was assumed that the accuracy of the product (evaluated against measurements in urban regions) is the same over urban and rural areas. Actual error in satellite-$PM_{2.5}$ in the rural region is not possible to determine unless the ground monitoring network expands to cover rural India in the future.

5. Conclusions

Switching to CCF for cooking and heating during pregnancy is expected to reduce the risk of LBW babies. Our study shows that this benefit will be lost if AAP levels continue to be high. Cohorts are required to elucidate the causal pathway for such intermediated effect. It will be important to address the issue of HAP and AAP simultaneously, especially in intervention areas where both are prevalent.

Data availability statements

The satellite-based $PM_{2.5}$ data that support the findings of this study can be available in the portal from the authors upon request.

The data that support the findings of this study are openly available at the following URL/DOI: www.dhsprogram.com/data/available-datasets.cfm.

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Ethical considerations

As this study is based on secondary data available in the public domain for research use, no ethical approval was required from any institutional review board.

Author contributions

RP conceived the study, curated the data, carried out the analysis, wrote the first draft, and edited and revised the text.

EC participated in data analysis.

SD, SG, and SDa provided inputs to carry out the analysis.

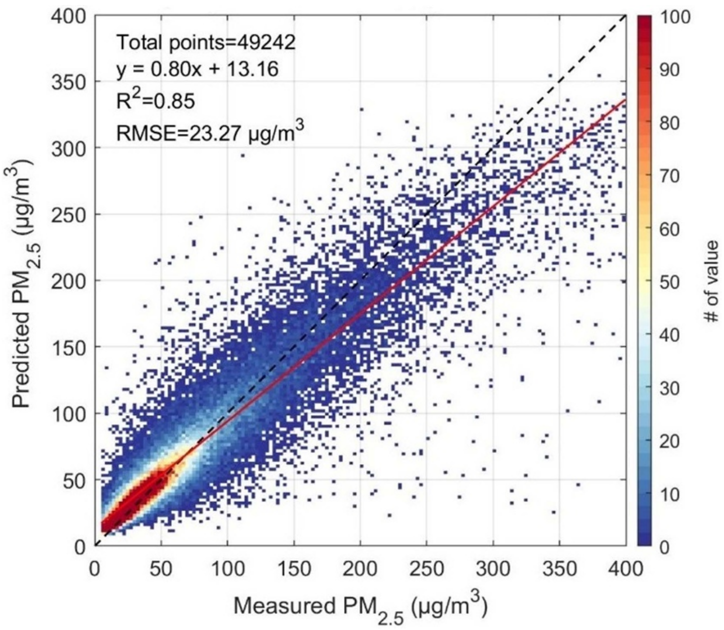
SD, AK, and EC provided the exposure assessments used in the analysis.

SD, SG, EC, AK, and SDa edited and revised the text.

Conflict of interest

The authors declare that they have no competing interests.

Appendix A



Validation of satellite derived daily $PM_{2.5}$ (on the Y-axis) against *in-situ* measurements (on the X-axis) from the Central Pollution Control Board (CPCB) network for the period from 2017–2021.

Appendix B. Sensitivity analysis by outcome measurement method

Outcome measurement method	By health card, ($n = 32\,809$)			By mother's recall, ($n = 19\,076$)		
Ambient $PM_{2.5}$ level (in $\mu g\ m^{-3}$)	aOR	95% CI	*P*	aOR	CI	*P*
Decile I (20, 37)	0.86	0.83–0.88	**<0.001**	0.8	0.77–0.83	**<0.001**
Decile II (37, 42)	0.87	0.85–0.90	**<0.001**	0.93	0.90–0.96	**<0.001**
Decile III (42, 46)	0.89	0.87–0.91	**<0.001**	0.9	0.87–0.93	**<0.001**
Decile IV (46, 51)	0.88	0.85–0.90	**<0.001**	0.91	0.88–0.95	**<0.001**
Decile V (51, 55)	0.96	0.94–0.99	**0.009**	0.93	0.89–0.96	**<0.001**
Decile VI (55, 62)	0.98	0.95–1.00	0.074	0.98	0.95–1.02	0.373
Decile VII (62, 70)	0.98	0.95–1.01	0.189	1.01	0.98–1.05	0.575
Decile VIII (70, 79)	0.98	0.96–1.01	0.256	1	0.96–1.03	0.847
Decile IX (79, 93)	0.98	0.95–1.01	0.179	1.02	0.99–1.06	0.147
Decile X (93, 144)	1.06	1.03–1.09	**<0.001**	1.02	0.99–1.05	0.185

(aOR—adjusted odds ratio of having LBW in women reporting primary use of clean cooking fuel, by ambient $PM_{2.5}$ level; CI—95% confidence interval; Bold values denote statistical significance at the $p < 0.05$ level.).

Appendix C. Sensitivity analysis by excluding cases with birth weight exceeding 4000 gm

	($n = 51\,489$)		
Ambient $PM_{2.5}$ level (in $\mu g\ m^{-3}$)	aOR	95% CI	P
Decile I (20, 37)	0.83	0.82–0.85	**<0.001**
Decile II (37, 42)	0.89	0.87–0.91	**<0.001**
Decile III (42, 46)	0.88	0.87–0.90	**<0.001**
Decile IV (46, 51)	0.89	0.87–0.91	**<0.001**
Decile V (51, 55)	0.94	0.92–0.96	**<0.001**
Decile VI (55, 62)	0.97	0.95–0.99	**0.011**
Decile VII (62, 70)	0.99	0.97–1.01	0.317
Decile VIII (70, 79)	0.99	0.96–1.01	0.219
Decile IX (79, 93)	1.01	0.99–1.03	0.551
Decile X (93, 144)	1.05	1.03–1.08	**<0.001**

(aOR—adjusted odds ratio of having LBW in women reporting primary use of clean cooking fuel, by ambient $PM_{2.5}$ level; CI—95% confidence interval; Bold values denote statistical significance at the $p < 0.05$ level.).

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