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Fine particulate matter air pollution and the mortality of children under five: a multilevel analysis of the Ethiopian Demographic and Health Survey of 2016

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Background: Every year, polluted air is costing the globe 543,000 deaths of children under five. The particulate matter below 2.5 μm diameter ($\text{PM}_{2.5}$) is a part of air pollution that has adverse effects on children's health. In Ethiopia, the effect of ambient $\text{PM}_{2.5}$ is least explored. This study aimed to assess the association between $\text{PM}_{2.5}$ and under-five mortality in Ethiopia.

Methods: The study used the data from the Ethiopian Demographic Health Surveys conducted in 2016, collected between January 18 and June 27. All children under five who had data on child mortality and location coordinates were included in the study. Exposure to ambient $\text{PM}_{2.5}$ concentration was a satellite-based estimate by the Atmospheric Composition Analysis Group at Washington and Dalhousie University, in the United States and Canada, respectively. Annual mean pollution levels and mortality datasets were matched by children's geographical location and dates of birth, death, and interview. The relationship between ambient $\text{PM}_{2.5}$ and under-five mortality was determined by a multilevel multivariable logistic regression on R software. The statistical analyses were two-sided at a 95% confidence interval.

Results: The study addressed 10,452 children with the proportion of under-five mortality being 5.4% (95% CI 5.0–6.8%). The estimated lifetime annual mean exposure of ambient total $\text{PM}_{2.5}$ was $20.1 \pm 3.3 \mu\text{g m}^{-3}$. A 10-unit increase in the lifetime annual mean ambient total $\text{PM}_{2.5}$ was associated with 2.29 [95% CI 1.44, 3.65] times more odds of under-five mortality after adjusting for other variables.

Conclusion: Children under five are exposed to higher levels of ambient $\text{PM}_{2.5}$ concentration, exceeding the limit set by the World Health Organization. Ambient $\text{PM}_{2.5}$ is significantly associated with under-five mortality, adjusting for other variables. Strong measures need to be taken to reduce air pollution.

KEYWORDS

particulate matter <2.5 μm (PM) 2.5, under-five children, air pollution, sub-Saharan Africa, Ethiopia, outdoor air pollution, Demographic Health Survey (DHS), Atmospheric Composition Analysis Group (ACAG)

Introduction

Every year, ambient air pollution is costing the globe around 3 million premature deaths while contributing to climate change and adverse economic impacts. The magnitude of pollution and its impact is higher in low- and middle-income countries (LMICs) (1). Ambient air pollution affects the entire population and all age groups, with children and the older adult being more susceptible (2).

Globally, among children under five, 543,000 deaths are attributed to both polluted indoor and outdoor air (3). Low nasal filtration, high ventilation rates, and higher metabolic rates in children might have contributed to a higher tendency of these pollutants to be deposited in them, consequently, affecting the lungs, renal and hepatic functions (4), and growth of the lungs (5). The burden is higher in Africa due to the higher consumption of polluting fuels, mainly biomass fuels (3).

Fine particulate matter of 2.5 μm diameter ($\text{PM}_{2.5}$) is one of the indicators of ambient air quality that is monitored (6, 7). Particulate matter (PM) is suspended particles in the ambient and indoor air that constitute both solid and liquid particles of any kind (8). Among children, short-term $\text{PM}_{2.5}$ exposure has been associated with pneumonia (9, 10) and upper and lower respiratory tract infection (ULRI) (10). $\text{PM}_{2.5}$ is also associated with an increase in viral and bacterial load (11), cough, wheezing, and lower respiratory infection in children (12). Pneumonia (3, 13–15) and acute respiratory illness are the leading causes of under-five mortality in the world (3). A longer time of exposure was associated with symptoms of cough, convulsion, or fever (16) and higher rates of all-cause under-five mortality in Nairobi (16) and western and central Africa (17) and infant mortality in sub-Saharan Africa (18). Most air pollution-related health impact assessments are based on long-term exposures including annual mean concentrations (19–21).

However, previous studies showing the strong relationship between ambient $\text{PM}_{2.5}$ and its detrimental human health effect have largely been conducted in developed nations; most are in North America and Europe. In developed nations, there is a relatively low air pollution status (22, 23) which might contribute to the small amount of mortality compared to developing countries. Hence, pooled estimates on the impact magnitude of ambient $\text{PM}_{2.5}$ from major studies conducted in the global north might be underestimated (18, 24, 25). This was apparent in the pooled estimates from a meta-analysis of studies from five WHO regions—estimates of $\text{PM}_{2.5}$ and all-cause mortality association showed 0.25 to 2.08% variations across the regions (22), China (23), and at the global level (25). In Africa, only a few studies have investigated and found that long-term exposure to ambient $\text{PM}_{2.5}$ was associated with child mortality (16–18, 26). Thus, further study helps to better understand the degree of the effect of ambient $\text{PM}_{2.5}$ in Africa.

Secondly, though under-five mortality has largely reduced since 2000 in sub-Saharan Africa, it remains the highest in need of urgent attention—75.8 deaths per 1,000 live births in 2019 (27, 28). Ethiopia is among the sub-Saharan African countries where the under-five mortality rate declined to 59 deaths per 1,000 live births in 2019 (29) from 116 deaths per 1,000 live births in 2006 (30, 31). The reduction was achieved due to improvements in sanitation, nutrition, and access to maternal and child health services. The 59 deaths per 1,000 live births is much higher than the aim or goal intended to be achieved, which is 25 deaths per 1,000 live births (32). The role of $\text{PM}_{2.5}$ in the death toll of under-five mortality is still a subject of debate. Thus, further studies will help to better explain the role of $\text{PM}_{2.5}$ on under-five mortality and reduce deaths (18).

Thirdly, due to the country's insubstantial monitoring stations, apparatus, and competency of technicians, there are minimal inquiries into ambient $\text{PM}_{2.5}$ and its adverse impact on health. Hence, there is a clear knowledge gap about ambient $\text{PM}_{2.5}$ and its relationship with under-five mortality in Ethiopia. To the best of our knowledge, this paper is the first in Ethiopia to investigate ambient $\text{PM}_{2.5}$ and its association with under-five mortality by controlling for individual characteristics.

Materials and methods

Study area and study design

Ethiopia is the largest landlocked country, with an estimated population of 110 million in the horn of Africa, located between 3°24' and 14°15' North and 33°00' and 48°00' East. It has nine regions and two cities divided for administrative purposes (33). The Ethiopian Demographic Health Survey (EDHS) followed a two-stage community-based cross-sectional study design. EDHS 2016 was collected from January 18 to June 27, 2016 (30).

Source and study population

The source population of the study was all children under five born 5 years before the survey period (January 2011 to June 2016) in Ethiopia. While all children under five born 5 years before the survey period in the selected Enumeration Areas (EAs) were the study population.

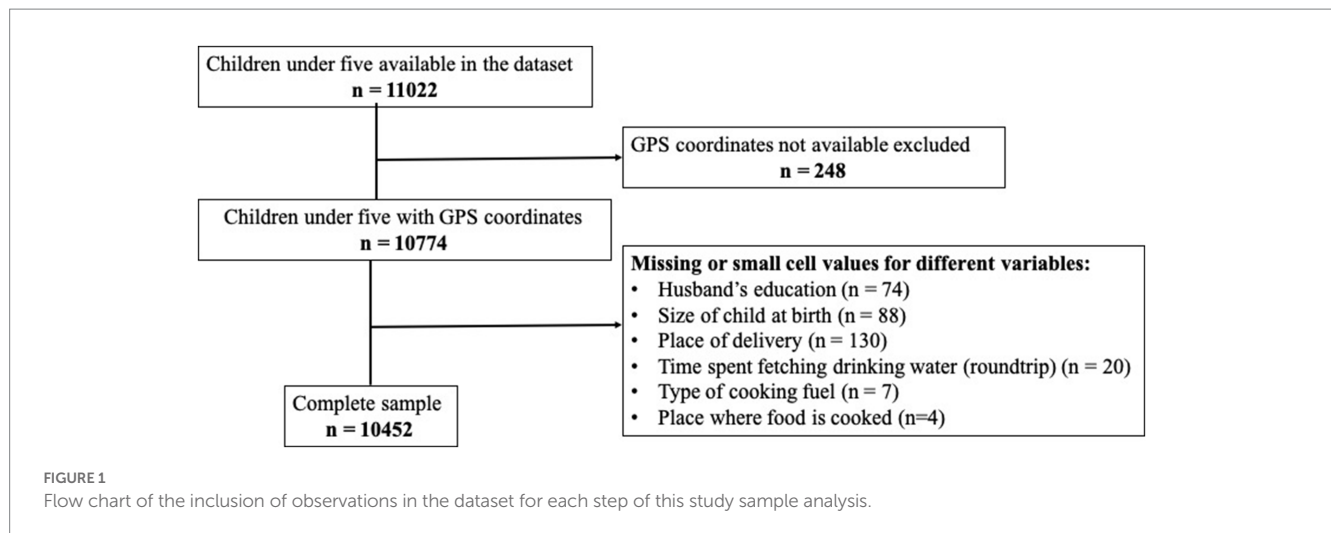
The inclusion criteria

All children under five born 5 years before the survey period in the selected households whose mortality data and cluster's Global Positioning System (GPS) coordinates were recorded in the EDHS dataset were included in this study. Children without mortality and geographical location coordinates information were excluded.

Sample size

The EDHS 2016 selected 645 EAs (202 urban and 443 rural EAs). Information was collected for 10,641 (11,022 weighted) children

Abbreviations: ACAG, Atmospheric Composition Analysis Group; AOD, Aerosol optical depth; AOR, Adjusted odds ratio; ARI, Acute respiratory illness; CI, Confidence interval; CRS, Coordinate Reference System; DHS, Demographic Health Survey; EA, Enumeration Area; EDHS, Ethiopian Demographic Health Survey; EEA, European Environment Agency; EU, European Union; GPS, Global Positioning System; ICC, Interclass correlation; LMICs, Low- and middle-income countries; PM, Particulate matter; $\text{PM}_{2.5}$, Particulate matter mass concentration size below 2.5 μm diameter; SD, Standard deviation; ULRI, Upper and lower respiratory tract infection among children; US, United States; VIF, Variance inflation factor; WHO, World Health Organization.



under five (30). After removing clusters with no location coordinates and data cleaning, a total of 9,856 (10,452 weighted) children under five were included in this study (Figure 1).

Ambient $PM_{2.5}$ concentration data derived from satellites were available across all geographical spaces in the study area.

Sampling procedures

The EDHS collects samples that are representative of both the regional and national levels as well as urban and rural areas. Its data is also to be comparable across different nations through standardized questionnaires. Households were selected after a list of first-level administrative units and their list of enumeration areas (EAs) was provided. We selected an equal number of households (28 households from each EA) from the registered list of households in the EAs using the systematic probability method. Information from all women aged 15–49 years (reproductive-aged women) was collected in all selected households. The women provided information about their children who were under five if they had any. The sampling, methodology, and procedure details have been found published elsewhere (30).

Data collection tools and procedures

The data of children under five needed for this study were retrieved from the Demographic Health Survey (DHS) website.¹ The dataset with filenames starting with ETBR (birth record), ETHR (a household record), ETPR (an individual record), and ETGE (geographical location) was downloaded. The EDHS 2016 interviewers used tablets (personal digital assistants) to enter the responses of study participants. The 2016 EDHS also used a standardized questionnaire by translating the questions into local languages and back to the original language. Interviewers were also calibrated by providing

training and frequent supervision before and during data collection, respectively (30).

Dependent variable

Under-five mortality also known as death before the age of 60 months was the dependent variable, with dichotomous values of “dead” or “alive.”

Exposure variable

Exposure to lifetime annual mean total $PM_{2.5}$ in $\mu g m^{-3}$ (microgram per cubic meter) atmospheric air is the main independent variable. In this study, “ $PM_{2.5}$ ” is a mixture of solid and liquid particles suspended in the ambient air” and its “mass concentration of particles diameter is less than 2.5 μm .”

Controlled variables

The socio-demographic (mother’s educational status, age of the mother, household wealth index, mother’s employment status, mother’s marital status, husband’s occupational status, husband’s educational level, and family size), individual/child-related (sex of the child, birth order, child age, size of the child at birth, plurality of a child, and place of birth), environmental-related [source of drinking water (categorized into “improved” and “unimproved”), type of toilet/latrine facility (“improved” and “unimproved”)—categorized according to the updated joint monitoring program (JMP),² presence of any kind of drinking water treatment in the household (“Yes” or “No”), type of cooking fuel (recorded as “clean fuels” if the fuel is liquefied petroleum gas (LPG), natural gas, biogas, or electricity; other kinds of cooking fuel are in the category

1 <https://dhsprogram.com/Data>

2 <https://washdata.org/monitoring/drinking-water>

of “solid fuels”), and place where food is cooked (“not inside the house,” “inside the house in a separate room,” or “inside the house not in a separate room”)], and community-level (region and residence) variables were controlled.

Data on children’s ambient total PM_{2.5} exposure

In Ethiopia, there is a limited air quality monitoring system (22, 34). Accordingly, in the absence of air quality monitoring systems (ground-based PM_{2.5} concentration data), satellite-based PM_{2.5} concentration estimates across the globe surface have been employed (22, 35). This study, therefore, used satellite-based PM_{2.5} concentration estimated by the Washington and Dalhousie Universities, Atmospheric Composition Analysis Group (ACAG). The ACAG at the universities produces estimates of PM_{2.5} across the globe, including Ethiopia, at 0.01° × 0.01° spatial resolution. The group estimates the ground-level PM_{2.5} from the year 1998 to 2019 using satellite remote sensing (NASA’s MODIS, MISR, and SeaWiFS) AOD retrievals and combining it with the chemical transport model (from GEOS-Chem). They also validate their estimate with land-based PM_{2.5} monitoring systems by employing Geographically Weighted Regression (GWR). The detailed estimation technique is published elsewhere (35). The V4.GL.02 version dataset was used, and it is available publicly for free and can be downloaded from <https://sites.wustl.edu/acag/datasets/surface-pm2-5/>. The annual mean PM_{2.5} concentration for the years from 2011 to 2016 was extracted from the downloaded ArcGIS-compatible raster datasets.

The lifetime annual mean total PM_{2.5} concentration exposure for each child was determined. For dead children, the lifetime annual mean total PM_{2.5} concentration was the exposure period of all the months up until death; for alive children, the lifetime annual mean total PM_{2.5} concentration was the exposure period up until the month EDHS 2016 data was collected.

The geographical coordinates of EAs’ were matched with the average annual total PM_{2.5} concentration data. The DHS randomly displaced the EAs’ geographical coordinates up to 2 km in urban and 5–10 km in rural areas to protect the respondents’ privacy. As a result, the average annual total PM_{2.5} within a circular radius of 3.3 km in urban areas and 6.7 km in rural areas was taken for each cluster. The month and year of the child’s date of death, birth, and interview were matched with the EAs’ average annual total PM_{2.5} concentration. A weighted total PM_{2.5} exposure was taken if the exposure period falls within two or more different years—the weighting procedure has been described in detail in previous studies (18, 26).

Data management procedures

The DHS datasets were merged using common/identifier variables (identification (ID), cluster, household, line, and birth number). R software version 3.6.3 was used to merge, recode, clean, and run descriptive and multilevel regression models while matching the geographical locations, raster clip, raster residual analysis, and sample raster values were performed using ArcGIS software version 10.7.

Data analysis

Before any analysis, the sample was weighted for the complex survey design (36), the variables were described, and sensitivity analysis was done. Sensitivity analysis is a method used to check the influence of the changes in the values of the independent variables (i.e., of missing values) on the bivariate relationship of the independent and dependent variables (37). Proportions across sub-groups and mean and standard deviations (SD) for continuous variables were used to summarize the variables.

A separate bivariate logistic regression model was built for each controlled variable and the lifetime annual mean PM_{2.5} exposure to assess their association with under-five mortality. Variables that showed a significance level of 15% were considered for the multilevel multivariate model. The degree of variation of under-five mortality among clusters was determined using two methods; the first method used was to compare the statistically significant difference between a null logistic regression and a null multilevel logistic regression model using EAs as random effect intercept. The second method used was to describe the heterogeneity of under-five mortality among clusters using interclass correlation (ICC). The ICC is “a measure of the proportion of variation in the outcome or under-five mortality that occurs between groups or clusters versus the total variation present” (38). In the multilevel multivariate logistic regression model, controlled variables have been added to the model step by step. Socio-demographic, child-related, environmental-related, and community-level variables were added to the model, respectively. Model assumptions were checked if they were met. The final model was selected by a backward stepwise variable selection technique. At each step, variables with a significance level of 15% and variance inflation factor (VIF) > 3 (39) were removed from the model. The selected final model had the highest log-likelihood. All statistical tests computed were two-sided tests at a 95% confidence interval.

Data quality and processing

The EDHS used re-interviewing households, checking one to two interviewers’ questionnaires per data collector, reviewing periodical field control table tools, dual entry of information by two different persons, and cleaning of missed values to ensure the quality of data (30). In this study, a careful dataset merging using dataset “identifier” or common variables, data quality parameters (36), and defensive coding while cleaning the data was done. Care was also taken in the choice of the coordinate reference system (CRS) and statistical packages (40).

Ethics approval and consent to participate

Permission was gotten from the DHS archive and geographic database to use the DHS data. The global estimate of annual mean PM_{2.5} concentration was made accessible to the public by the ACAG and was used for free. Furthermore, the study was approved by the College of Health Sciences of Addis Ababa University Ethical Review Committee with a reference number SPH/1119/13.

TABLE 1 Socio-demographic factors of the study participants EDHS 2016, $n=10,452$.

	Total population		Under-five mortality		P^{**}
	n	%	Dead (%)	Alive (%)	
Socio-demographic factors					
Age of the mother					0.31
15–24	2,271	21.7	5.9	94.1	
25–29	3,192	30.5	5.8	94.2	
30–34	2,372	22.7	5.1	94.9	
≥35	2,617	25.0	6.4	93.6	
Mother's education					<0.001*
No education	6,858	65.6	6.5	93.5	
Primary	2,823	27.0	5.0	95.0	
Secondary and above	771	7.4	3.8	96.2	
Mother's current marital status					0.88
Not in a union/not living with a partner	535	5.1	6.0	94.0	
In a union/living with a partner	9,917	94.9	5.8	94.2	
Mother's employment status					0.36
Not working	5,806	55.5	6.0	94.0	
Working	4,646	44.5	5.6	94.4	
Wealth index					<0.001*
Poorest	2,428	23.2	7.2	92.8	
Poorer	2,373	22.7	6.1	93.9	
Middle	2,173	20.8	5.3	94.7	
Richer	1,926	18.4	6.1	93.9	
Richest	1,552	14.9	3.3	96.7	
Husband's education					0.003*
No education	4,739	47.8	6.6	93.4	
Primary	3,945	39.8	5.5	94.5	
Secondary and above	1,233	12.4	4.4	95.6	
Husband's employment status					0.15
Not working	737	7.4	6.9	93.1	
Working	9,180	92.6	5.7	94.7	
Family size					<0.001*
≤three	5,078	48.6	6.9	93.1	
Above three	5,374	51.4	4.7	95.3	
Sex of household head					0.47
Female	1,434	13.7	5.5	94.5	
Male	9,018	86.3	5.9	94.1	

**A bivariate logistic regression. *Used in the multilevel multivariate analysis.

Results

Characteristics of respondents

The size of the sample included in this study analysis was 10,452. The overall children's mothers' age mean (SD) was 29.6 ± 6.6 . Children's mothers between 25 and 29 years old constituted the majority, 29.9%. Most of the children's mothers were married or living with a partner (94.9%), not working (55.5%), with no education status

(65.6%), and had the poorest wealth index (23.2%). The study participants with a man as the head of the household (86.3%), a family size above three (51.4%), a husband with no education (47.8%), and a working husband (92.6%) were also the majority (Table 1).

The total sample size proportion of under-five mortality was 5.4% (95% CI 5.0–5.8%). According to respondents, 52% of the children under five were boys, 41.6% had average birth weight, 2.5% were twins, and 26.7% were born in institutions. Children's age mean \pm SD in months was 27.8 ± 18.7 , the category ≥ 24 months constitutes 54.5% (Table 2).

TABLE 2 Child-related factors of the study participants EDHS 2016, $n=10,452$.

	Total population		Under-five mortality		P^{**}
	n	%	Dead (%)	Alive (%)	
Child/individual factors					
Sex of the child					<0.001*
Female	5,018	48.0	4.9	95.1	
Male	5,434	52.0	6.7	93.3	
Size of the child at birth					<0.001*
Very large	1,891	18.1	6.8	93.2	
Large	1,466	14.0	4.8	95.2	
Average	4,351	41.6	5.0	95.0	
Small	1,059	10.1	5.9	94.1	
Very small	1,685	16.1	7.8	92.2	
Child age (in months)					<0.001*
≤12	2,823	27.0	18.3	81.7	
12–24	1,934	18.5	3.6	96.4	
>24	5,695	54.5	0.5	99.5	
Birth order					0.06*
Third and below	5,121	49.0	5.4	94.6	
Fourth and above	5,331	51.0	6.3	93.7	
The plurality of a child					<0.001*
Yes	265	2.5	20.4	79.6	
No	10,187	97.5	5.4	94.6	
Place of delivery					<0.001*
Home	7,662	73.3	6.7	93.3	
Institution	2,790	26.7	4.0	96.0	

**A bivariate logistic regression. *Used in the multilevel multivariate analysis.

The lifetime annual mean satellite-based ambient $PM_{2.5}$ exposure among children under five was $20.1 \pm 3.3 \mu g m^{-3}$. The majority (67.2%) of households collect their drinking water within ≤ 30 min roundtrip distance. The proportion of households with improved drinking water sources, improved toilet facilities, and clean fuel was 56.8, 5.1, and 3.4%, respectively. Most (80.9%) of the respondents were residing in rural areas (Table 3).

Determining the association between ambient $PM_{2.5}$ concentration and under-five mortality in Ethiopia

In the bivariate logistic model of lifetime annual mean $PM_{2.5}$ and under-five mortality, the lifetime annual mean $PM_{2.5}$ showed a significant association with under-five mortality ($p=0.001$) (Table 3).

Fitting multilevel multivariate logistic regression model

There was a significant difference between the null multilevel logistic regression model, EAs being the random effect intercept, and

the empty logistic regression model (value of $p < 0.001$). The ICC and the random effect intercept variance of the null model were 10.0% and 0.34, respectively.

The final model selected based on the criteria set prior to analysis was Model 4, as seen in Table 4. In the final model, a 10-unit increase in lifetime annual mean exposure to ambient $PM_{2.5}$ was associated with 2.29 [95%CI 1.44–3.65] times more odds of being dead, adjusting for all other variables (Table 4).

Moreover, in the final model (Model 4), children under five with mothers without formal education ($p=0.02$), very large birth size ($p=0.04$), those who were twins ($p < 0.001$), those born at home ($p < 0.001$), those whose food was cooked inside a house without a separate room ($p=0.001$), and residing in the Somali ($p=0.002$), Harari ($p=0.02$), and Dire Dawa ($p=0.02$) regions were more likely to die, compared with those whose mothers had a secondary and above education, a large birth size, singletons, delivered in an institution, whose food was cooked outside of the house, and resided in the Tigray region, respectively; the results were statistically significant. In contrast, children under five with a family size above three ($p < 0.001$), were between 12 and 24 months ($p < 0.001$), age ≥ 24 months ($p < 0.001$), and were girls ($p < 0.001$) were less likely to die, compared with a family size ≤ 3 , age ≤ 12 , and being a boy under five, respectively; the results were statistically significant (Table 4).

TABLE 3 Environmental-related and community-level factors of the study participants EDHS 2016, $n=10,452$.

	Total population		Under-five mortality		<i>P</i> **
	<i>n</i>	%	Dead (%)	Alive (%)	
Environmental factors					
Ambient PM_{2.5} (mean ± SD)	20.1 ± 3.3	21.7 ± 5.2	20.0 ± 3.3	0.001	20.1 ± 3.3
Source of drinking water					0.009*
Improved	5,940	56.8	5.3	94.7	
Unimproved	4,512	43.2	6.6	93.4	
Time to fetch (roundtrip in minutes)					0.02*
≤30	7,018	67.2	5.4	94.6	
>30	3,434	32.8	6.6	93.4	
Any kind of household water treatment					0.31
Yes	881	8.4	5.1	94.9	
No	9,571	91.6	5.9	94.1	
Type of toilet facility					<0.01
Improved	533	5.1	3.1	96.9	
Unimproved	9,919	94.9	6.1	93.9	
Type of cooking fuel					<0.001*
Clean fuel	352	3.4	2.3	97.7	
Solid fuel	10,100	96.6	6.0	94.0	
The place where food is cooked					<0.001*
Outside the house	5,978	57.2	5.1	94.9	
Inside but in a separate room	711	6.8	5.0	95.0	
Inside but not in a separate room	3,763	36.0	7.6	92.4	
Community-level variables					
Type of place of residence					<0.001*
Urban	1,179	11.3	3.1	96.9	
Rural	9,273	88.7	6.5	93.5	
Region					<0.001*
Tigray	679	6.5	3.8	96.2	
Afar	112	1.1	8.7	91.3	
Amhara	2,009	19.2	4.8	95.2	
Oromia	4,628	44.3	5.5	94.5	
Somali	351	3.4	6.4	93.6	
Benishangul	115	1.1	7.4	92.6	
SNNPR	2,227	21.3	5.4	94.6	
Gambela	25	0.2	6.1	93.9	
Harari	25	0.2	6.9	93.1	
Addis Ababa	238	2.3	2.7	97.3	
Dire Dawa	43	0.4	5.5	94.5	

**A bivariate logistic regression. *Used in the multilevel multivariate analysis.

Discussion

This study assessed the relationship between long-term exposure to ambient fine particulate concentration levels and the mortality of children under five in Ethiopia. The study used a community-based two-stage survey design and satellite-based ambient PM_{2.5} exposure

level. Total PM_{2.5} is significantly and positively associated with under-five mortality. It found that the annual mean ambient total PM_{2.5} children are exposed to is higher than the health-recommended concentration level. These findings revealed PM_{2.5} plays a significant role in the burden of under-five mortality. The results also provide insights for the government on the importance of increasing its effort

TABLE 4 Multivariable multilevel logistic regression analysis of PM_{2.5} and other factors associated with under-five mortality, EDHS 2016, n=10,452.

	Under-five mortality (%)	AOR** 95% CI	AOR*** 95% CI	AOR**** 95% CI
		Model 2	Model 3	Model 4
PM _{2.5} (µg m ⁻³) (mean ± SD)**	21.7 ± 5.2	1.34 (1.07, 1.66)*	1.33 (1.07, 1.66)*	2.29 (1.44, 3.65)*
Mother's education				
No education	6.5	1.58 (1.08, 2.31)*	1.74 (1.15, 2.62)*	1.65 (1.08, 2.54)*
Primary	5.0	1.15 (0.78, 1.69)	1.15 (0.78, 1.73)	1.10 (0.72, 1.67)
Secondary and above	3.8	(Reference)		
Wealth index				
Poorest	7.2	2.08 (1.49, 2.89)*	1.24 (0.85, 1.80)	0.80 (0.48, 1.33)
Poorer	6.1	1.84 (1.29, 2.63)*	1.18 (0.79, 1.74)	0.88 (0.53, 1.45)
Middle	5.3	1.59 (1.09, 2.32)*	1.10 (0.73, 1.66)	0.86 (0.52, 1.44)
Richer	6.1	1.95 (1.35, 2.82)*	1.29 (0.86, 1.93)	1.12 (0.68, 1.85)
Richest	3.3	(Reference)	(Reference)	(Reference)
Family size				
≤three	6.9	(Reference)	(Reference)	(Reference)
Above three	4.7	0.55 (0.46, 0.66)*	0.57 (0.47, 0.70)*	0.58 (0.47, 0.71)*
Sex of the child				
Female	4.9		0.67 (0.55, 0.81)*	0.66 (0.55, 0.80)*
Male	6.7		(Reference)	(Reference)
Size of the child at birth				
Very large	6.8		1.43 (1.01, 2.04)*	1.46 (1.03, 2.09)*
Large	4.8		(Reference)	(Reference)
Average	5.0		0.88 (0.64, 1.20)	0.92 (0.67, 1.26)
Small	5.9		0.94 (0.62, 1.42)	1.01 (0.66, 1.53)
Very small	7.8		0.94 (0.66, 1.33)	0.99 (0.70, 1.41)
Child age (in months)				
≤12	18.3		(Reference)	(Reference)
12–24	3.6		0.16 (0.12, 0.21)*	0.16 (0.12, 0.21)*
>24	0.5		0.02 (0.01, 0.03)*	0.02 (0.01, 0.03)*
The plurality of a child				
Yes	20.4		5.57 (3.71, 8.36)*	5.41 (3.59, 8.16)*
No	5.4		(Reference)	(Reference)
Place of delivery				
Home	6.7		2.35 (1.81, 3.05)*	2.21 (1.69, 2.90)*
Institution	4.0			(Reference)
The place where food is cooked				
Outside the house	5.1			(Reference)
Inside but in a separate room	5.0			1.17 (0.72, 1.86)
Inside but not in a separate room	7.6			1.49 (1.17, 1.90)*
Type of residence				
Urban	3.1			(Reference)
Rural	6.5			1.64 (0.99, 2.72)
Region				
Tigray	3.8			(Reference)
Afar	8.7			0.78 (0.43, 1.43)

(Continued)

TABLE 4 (Continued)

	Under-five mortality (%)	AOR** 95% CI	AOR*** 95% CI	AOR**** 95% CI
		Model 2	Model 3	Model 4
Amhara	4.8			0.79 (0.46, 1.34)
Oromia	5.5			1.11 (0.67, 1.84)
Somali	6.4			2.89 (1.48, 5.65)*
Benishangul	7.4			1.55 (0.92, 2.59)
SNNPR	5.4			1.22 (0.72, 2.06)
Gambela	6.1			1.36 (0.77, 2.38)
Harari	6.9			2.08 (1.12, 3.86)*
Addis Ababa	2.7			0.99 (0.44, 2.21)
Dire Dawa	5.5			2.21 (1.17, 4.18)*
Random effects				
ICC in %		7.6	5.9	5.6
Model comparison				
Log-likelihood		-2130.6	-1581.8	-1566.2

Ten-unit increase. Statistically significant at $p < 0.05$. **Adjusted for socio-demographic variables. *Adjusted for socio-demographic and child-related variables. ****Adjusted for socio-demographic, child-related, environmental-related, and community level variable. Model 1 was built previously separately for each controlled variable.

in monitoring air quality to reduce its pollution level and negative effect on health.

The lifetime annual mean satellite-based ambient $PM_{2.5}$ children are exposed to in their lifetime was $20.1 \pm 3.3 \mu g m^{-3}$. This is beyond the World Health Organization (WHO) 2021 guideline—which updated the 2005 global air quality guideline—annual exposure limit of $5 \mu g m^{-3}$ (20). The result is consistent with evidence from LMICs such as China, India, Pakistan, Bangladesh (19), Africa, and Eastern Mediterranean (3) where almost no population, including children under five, breathe air below $10 \mu g m^{-3}$ $PM_{2.5}$ concentration. Higher levels of $PM_{2.5}$ is still a problem in European Member (EU) states too. According to the European Environment Agency (EEA), 97% of European urban residents are exposed to $PM_{2.5}$ higher than $5 \mu g m^{-3}$. The road transport, energy, industry, and agriculture sectors are the sources of $PM_{2.5}$ in Europe (41). In China and India, however, coal, construction dust, and burning solid fuels are the major emitters of $PM_{2.5}$ (19, 23). In Ethiopia, most households—almost 70% in urban and 99% in rural areas—depend on solid fuels, mainly woody biomass, animal dung, and crop stalks (29). A study conducted on source apportionment of $PM_{2.5}$ in Addis Ababa found that traffic flow, biomass, and dust sources are the major constituents (42).

Adjusting for other variables, a $10 \mu g m^{-3}$ increase in ambient $PM_{2.5}$ was significantly associated with more odds of death. Furthermore, children in households whose food was cooked outside of the house, with mothers without formal education, who had a very large birth size, who were twins, and who were born at home were found to be significantly and positively associated with under-five mortality. On the contrary, children with a family size above three, between 12 and 24 months, age ≥ 24 months, and who were girls were significantly and negatively associated with under-five mortality.

A significant association between a $10 \mu g m^{-3}$ increase in ambient $PM_{2.5}$ and under-five mortality that was found in this study is consistent with previous studies in India (43), Asia (44, 45), and sub-Saharan Africa (26). However, there is a difference between previous studies and this study's estimated effect sizes; there was an

increase in odds of under-five mortality with a 10-unit increase in lifetime annual mean $PM_{2.5}$ concentration, adjusting for other variables (17, 46). This might be attributed to the use of different definitions—death per 1,000 live births—, separate estimations for the different types of $PM_{2.5}$ (total $PM_{2.5}$ versus salt and dust removed $PM_{2.5}$), and differences in adjusted variables. It may also be because the estimate by Karimi and Shokrinezhad (46) was a pooled estimate, and the majority of studies included were from developed nations. The magnitude of the effect of $PM_{2.5}$ on under-five mortality is higher among developing and least developed countries compared to developed countries (47). Fine particulate matter, as a result of its smaller mass concentration diameter size, can penetrate the blood-gas barrier. This allows the different chemical constituents of $PM_{2.5}$ to circulate in the blood system and reach the different human organs (48). Especially, $PM_{2.5}$ deposition in children is higher due to their fast breathing, lower nasal filtration, higher metabolic rate, and limited ability to metabolize toxic pollutants (4). Different substances, i.e., organic matter, elemental carbon, soil dust, sulfate, nitrate, and ammonium ions, form $PM_{2.5}$ although it varies from place to place (49). Nephrotoxic heavy metals—chromium and cadmium—components of $PM_{2.5}$ can also reach the kidney to affect its function (50), which might lead to death. $PM_{2.5}$ is also associated with notable under-five mortality killer diseases pneumonia (3, 9, 14) and ARI (14, 15, 51).

Environmental-related variables—the type of drinking water source, toilet facility, and cooking fuel—were not significant in the final model. The following reasons could be the important factors that come into play. First, not all sources labeled as improved drinking water are free of fecal or disease-causing organisms (52). Second, there is a reintroduction of microbes into drinking water during collection by contaminated hands, containers, utensils, and/or insects (53, 54). Finally, households with improved drinking water may not necessarily have improved toilet facilities or vice versa (55). Even after access to improved facilities, the quality is influenced by human behavior, i.e., hand washing, personal hygiene, and consistent use of improved

facilities (53, 54). Similarly, the use of clean fuel does not mean households are well-ventilated and the indoor air is relatively acceptable (56). This study supports the statement. Cooking food inside a house with no separate room, a proxy to ventilation, was associated with higher odds of under-five mortality.

Strengths and limitation

The study provides insights into the relationship between ambient PM_{2.5} concentration level and under-five mortality at the individual level for the first time, and to the best of our knowledge, at the national level in Ethiopia. The study overcame the absence of ground-level ambient PM_{2.5} concentration data by using a freely available satellite-based estimate of ACAG.

The study is limited in accounting for indoor stay (PM_{2.5} exposure from indoor air was not quantified) and the movement of children from place to place in determining exposure to ambient PM_{2.5}. It is also limited in not using ground-based PM_{2.5} nor making adjustments to the retrieved satellite-based PM_{2.5} as it is subject to measurement error. Currently, ground-based data is assumed to be a gold standard relative to satellite-based data. The authors compared the annual mean PM_{2.5} from satellite-based measurements and the three land-stationed BAM PM_{2.5} monitors in Addis Ababa (57) for similar geographical points. A large concentration difference was noticed at Tikur Anbessa Specialized Hospital and International Community School. However, a similar concentration level was observed at the United States (US) Embassy in Addis Ababa. A difference is expected considering that validated satellite-based PM_{2.5} has used a small number of land stations in Africa, including Ethiopia (58, 59). As a result, caution should be taken in interpreting the results of this study.

Conclusion

This study determined the annual mean ambient PM_{2.5} exposure of children under five in their lifetime. Fine particulate matter annual exposure concentration among children under five exceeded the WHO recommended level. Ambient PM_{2.5} was significantly associated with higher odds of under-five mortality, adjusting for other variables. These results support the importance of taking measures to improve ambient air quality. The government should take strong actions to reduce air pollution and help achieve the goal set to decrease under-five mortality. The authors recommend further investigation which considers movement and indoor stay in determining ambient PM_{2.5} exposure in Ethiopia. It is also recommended to identify which constituents of PM_{2.5} are greatly affecting under-five mortality in Ethiopia.

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Data availability statement

Publicly available datasets were analyzed in this study. This data can be found at: <https://dhsprogram.com/Data>, <https://sites.wustl.edu/acag/datasets/surface-pm2-5/>.

Ethics statement

The studies involving human participants were reviewed and approved by the College of Health Sciences of Addis Ababa University Ethical Review Committee. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

ABS did the study design, data acquisition, data cleaning, data analysis, and interpretation and contributed to the drafting, revising, and editing of this manuscript. AK and WT participated in the principal supervision, interpretation, and revision of the final manuscript. All authors read and approved the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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