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Early life ambient air pollution, household fuel use, and under-5 mortality in Ghana

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ABSTRACT

Introduction: Environmental exposures, such as ambient air pollution and household fuel use affect health and under-5 mortality (U5M) but there is a paucity of data in the Global South. This study examined early-life exposure to ambient particulate matter with a diameter of 2.5 µm or less ($PM_{2.5}$), alongside household characteristics (including self-reported household fuel use), and their relationship with U5M in the Navrongo Health and Demographic Surveillance Site (HDSS) in northern Ghana.
Methods: We employed Satellite-based spatiotemporal models to estimate the annual average $PM_{2.5}$ concentrations with the Navrongo HDSS area (1998 to 2016). Early-life exposure levels were determined by pollution estimates at birth year. Socio-demographic and household data, including cooking fuel, were gathered during routine surveillance. Cox proportional hazards models were applied to assess the link between early-life PM2.5 exposure and U5M, accounting for child, maternal, and household factors.
Findings: We retrospectively studied 48,352 children born between 2007 and 2017, with 1872 recorded deaths, primarily due to malaria, sepsis, and acute respiratory infection. Mean early-life $PM_{2.5}$ was 39.3 µg/m^3, and no significant association with U5M was observed. However, Children from households using “unclean” cooking fuels (wood, charcoal, dung, and agricultural waste) faced a 73 % higher risk of death compared to those using clean fuels (adjusted HR = 1.73; 95 % CI: 1.29, 2.33). Being born female or to mothers aged 20–34 years were linked to increased survival probabilities.
Interpretation: The use of “unclean” cooking fuel in the Navrongo HDSS was associated with under-5 mortality, highlighting the need to improve indoor air quality by introducing cleaner fuels.

1. Introduction

Under-5 mortality (U5M) is of global public health importance. It is a significant metric for assessing children’s health for stakeholders and policymakers, as well as a key indicator for the quality of healthcare and social advancements (Hageman, 2019). In 2015, the United Nations adopted the Sustainable Development Goals (SDGs) (van Donkelaar et al., 2016) of which SDG 3.2 aims to eliminate preventable child deaths by 2030 and U5M to at most 25 per 1000 live births. So far, according to the 2022 United Nations Inter-Agency Group for Child Mortality Estimation (UN IGME), U5M in Sub-Saharan Africa (SSA) dropped by 15 % from 2015 to 2021 to 74 deaths per 1000 live births and for Ghana by 21 %; to a rate of 44 deaths per 1000 live births in 2021. At this rate of reduction, the set targets may not be achieved (Alkema L, New JR, Pedersen J, You D, Estimation UNI agency G for CM, Group TA. Child mortality estimation, 2013).

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Ambient air pollution is a significant environmental problem, contributing to an estimated 6.67 million deaths worldwide in 2019, equivalent to 11.6 % of total global deaths (Institute, 2020). Exposure to polluted air can cause respiratory diseases, such as asthma and bronchitis, and has been shown to affect brain and nervous system development in early life (Lončar et al., 2022). Further, environmental exposures, are estimated to cause approximately 26 % of U5M according to the United Nations International Children's Emergency Fund (SAGE Publications, 2020).

In Ghana, air pollution is a growing concern, with high levels of particulate matter (PM) and other harmful pollutants in the air (Gumy and Mudu, 2018). According to the latest available data, the country's annual mean PM$_{2.5}$ concentration is 35 µg/m^3, far exceeding the WHO recommended air quality guideline of 5 µg/m^3 (WHO. www.who.int., 2022). Outdoor air pollution is mainly caused by the burning of waste, agricultural activities and the seasonal harmattan dust (Moro et al., 2022; Dickinson et al., 2015), whereas indoor air pollution is largely caused by the lack of proper ventilation and reliance on traditional cooking stoves and biomass fuels. Socio-economic factors such as poverty, education, as well as access to healthcare among others also contribute to the burden of disease and health in Ghana (de-Graft Aikins et al., 2014) These factors can exacerbate the negative health effects of air pollution, particularly in children and other vulnerable populations (Hajat et al., 2015).

Globally, several epidemiological studies have linked environmental pollutants like PM$_{2.5}$, Carbon Monoxide, Nitrogen oxides, etc to unfavorable birth outcomes such as preterm birth, low birth weight and ultimately death (Bekkar et al., 2020; Cai et al., 2020; Fleischer et al., 2014). There is also a growing body of literature on the adverse health effects and birth outcomes of air pollution in high-income countries (Pedersen et al., 2013; Franklin et al., 2019). However, research on the impact of air pollution on child health in low- and middle-income countries, especially in Africa and Ghana, is still limited. This highlights the need for more research to better understand the relationship between contextual environmental and social factors (such as poverty, fuel type use, education, and access to health care) and child health outcomes, and to develop effective interventions to address these issues in resource-limited settings.

The aim of the current study is to examine the relationship between ambient air pollution, household fuel use and under-5 mortality in the coverage area of the Navrongo Health and Demographic Surveillance Site in Northern Ghana and the potential role of social determinants in this associations.

2. Methods

2.1. Study setting

The Navrongo Health and Demographic Surveillance System (NHDSS, Fig. 1), operates within the Kasena Nankana Municipal and West districts of northern Ghana (Oduro et al., 2012; Moro, 2020). It covers a land area of 1,675 km^2 with an estimated population of 170,000 people living in over 32,000 households. The major source of income is rain-fed subsistence agriculture, and much of the area (approximately

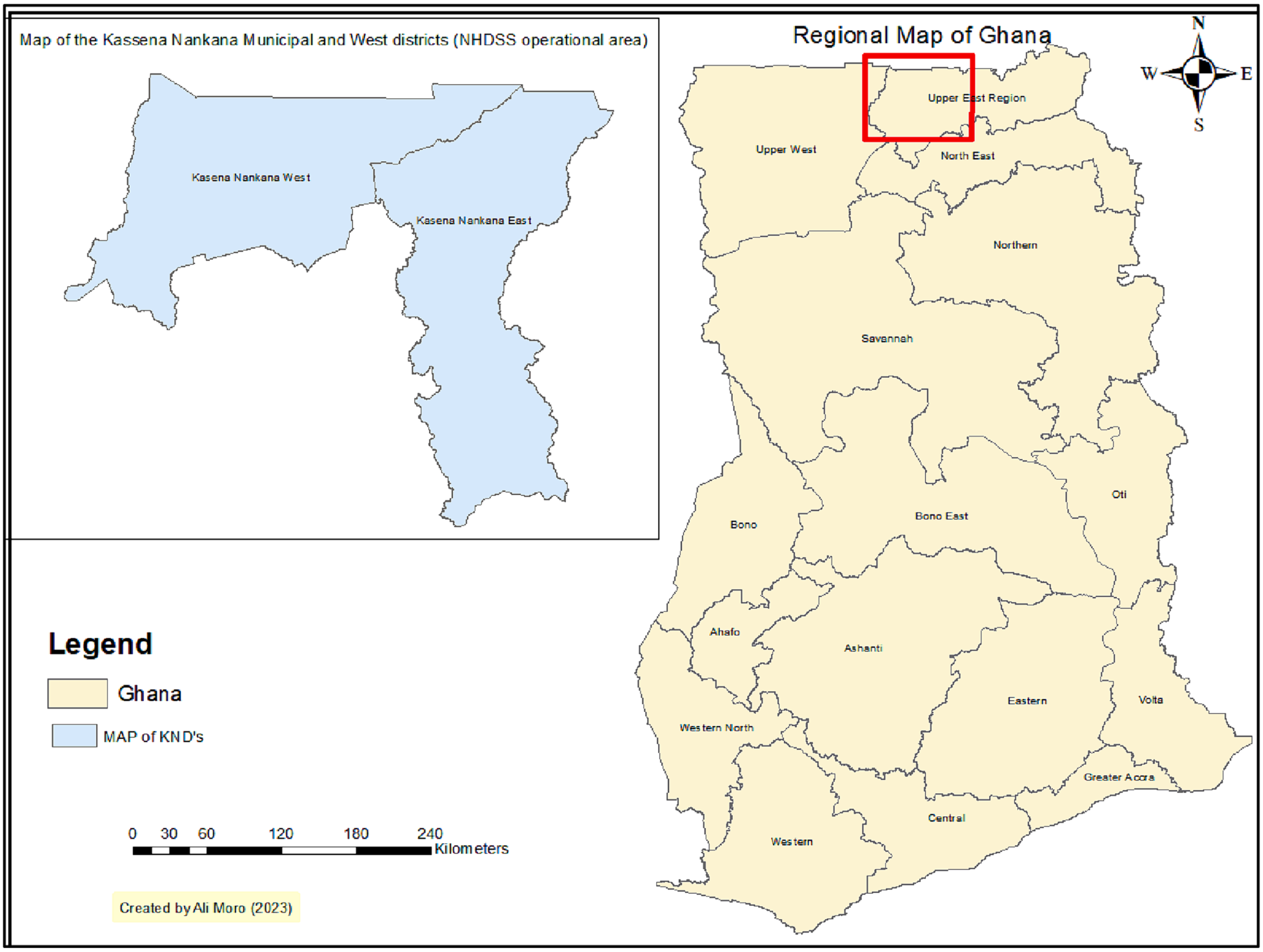

Fig. 1. Map of Ghana and the study area (Kasena Nankana Municipal Assembly and Kasena Nankana Wes District); KND's, Kasena Nankana Districts.

80 %) is rural (Oduro et al., 2012; Moro, 2020) except the *peri*-urban Navrongo area. Food insecurity is cyclic, with periods of abundance and scarcity. The NHDSS area is equipped with essential health infrastructure, comprising two district hospitals, five health centers, and multiple CHPs and clinics. Climatically, the area is characterized by a single rainy season from May to October and a prolonged dry season, which is also characterized by seasonal harmattan winds (north-east trade winds) that blow dust in from the Sahara (Moro et al., 2022).

Residents living within the operational area of the NHDSS are under continuous demographic surveillance. Families are visited twice a year to gather data on births, deaths, pregnancies, marriages, in and out-migrations (Oduro et al., 2012). Other information gathered includes socio-demographic factors, such as sex, age, maternal education, and household socioeconomic position.

2.2. *Ethical clearance*

The Navrongo HDSS has approval from the Navrongo Health Research centers Institutional Review Board (NHRC-IRB). Compound and household heads provide consent before their units are included in the HDSS. Additional ethical approval for the current study was obtained from the NHRC-IRB (approval number: #NHRCIRC486).

2.3. *Exposure: Ambient pollution*

The GPS co-ordinates of households at birth were spatially joined to predict annual average concentrations of $PM_{2.5}$ (including a variant with dust and sea-salt algorithmically removed) via geographic software (ArcGIS v 10.1). Predictions of ambient $PM_{2.5}$ were derived using satellite-based spatio-temporal models which are fully described elsewhere (Geddes et al., 2015). Briefly, global maps of ambient $PM_{2.5}$ were generated by integrating data from the Moderate Resolution Imaging Spectroradiometer (MODIS), Multi-angle Imaging Spectroradiometer, and Sea-Viewing Wide Field-of-View Sensor satellites – giving a near continuous planetary surface of PM_{25}. These values were converted to ground-level concentrations through the application of GEOS-Chem chemical transport model and ground-based sun photometer observations. Generated ground values (at an approximate resolution of 1 km by 1 km) were produced for the years 1998 to 2016. The current study used the pollution estimates at the year of birth as the measure for early life exposure levels for study individuals. Periods outside the available windows were assigned by using the closest available year. Therefore, children born in 2017 were assigned exposures from 2016**.** A variant model, with dust and sea-salt algorithmically removed, was utilized in sensitivity analyses. The correlation for the pollution with dust and pollution without dust and sea salt was 0.65.

2.4. *Outcome: Mortality data and ascertainment of cause of death*

We examined overall and cause-specific mortality among children under-5 years from January 2007 to December 2017 in the NHDS. Deaths are identified by community-based key informants who notify trained field staff stationed in the various communities. Following notification of a death, a trained and experienced field supervisor is dispatched to conduct a Verbal Postmortem (VPM). Verbal Postmortems were performed utilizing the standardized International Network of field sites with continuous Demographic Evaluation of Populations and Their Health (INDEPTH) (Findley, 2017) verbal autopsy form approved by WHO. The completed VPMs are coded by two physicians independently to determine the cause of death using the International Classification of Disease, 10th revision (ICD-10) system. In case of disagreement a third physician is consulted to reach a resolution (Aborigo et al., 2013; Welaga et al., 2013).

2.5. *Additional explanatory variables*

Children were prospectively followed from birth until they reached the age of five, experienced mortality, migrated out of the study area, or until the conclusion of the analysis period on December 31st, 2017. At the end of the follow-up period and after censoring, the age categories included neonates (0–28 days), infants (1–11 months), and children (1–5 years). Various child-related data were considered, such as sex (male or female), birth order (1, 2–4, and 5 +), and twin status (singleton or multiple).

Maternal factors comprised the age of the mother, ethno-linguistic status, marital status, educational level attained, and religious affiliation. Additionally, other community and household factors were considered including the place of birth (home vs. health facility), residence of the mother (rural or urban), and household socioeconomic status categorized as poorest, poorer, poor, less poor, and least poor. The wealth index was derived through principal component analysis (PCA) using household assets to estimate socioeconomic status (Welaga et al., 2013). Over 25 distinct items were considered in this analysis, ranging from substantial holdings like land and car ownership to smaller household possessions such as radios and fans.

Furthermore, variables pertaining to personal exposures to household air pollution were collected, encompassing the types of fuels used for cooking or lighting. Unfortunately, insufficient information on household lighting was available for further analysis so a focus was instead placed on cooking fuels as a proxy for household air pollution exposure. In particular, the distinction was made between clean cooking methods, such as electricity and liquefied petroleum gas (LPG), and unclean cooking methods, including the use of agricultural residues, animal droppings, wood, or charcoal.

2.6. *Statistical analyses*

Categorical data is reported as absolute counts with respective proportions. Differences between groups were determined using Pearson's Chi-squared test. Cross-tabulations were performed for comparison of study variables across groups. For continuous data, averages (mean ± standard deviation) were calculated. Univariable and multivariable Cox proportional hazards models were developed to examine the association between early life $PM_{2.5}$, household fuel use, baseline socio-demographic factors and under-five mortality. Separate models were created for $PM_{2.5}$ and household fuel use in addition to a model with both $PM_{2.5}$ and fuel use together. Model construction and confounder/covariate selection was based on a combination of a priori variables of interest such as wealth index, and rurality and examination of model diagnostics. The final models included gender and maternal age in addition to $PM_{2.5}$ and cooking fuel use. Additional socio-economic indicators such as maternal education, place of residence, and wealth index violated the proportional hazards assumption (Supplementary figure S3) and as such were not included in the final models. However, sensitivity analysis where wealth index (representing overall socio-economic position and collapsed into most wealthy versus all others), education (any versus none) and residence (urban/rural: which is determined by NHDSS by multiple factors, including the geographic location [cluster of houses located in the Central zone of the NHDSS thus an approximate radius of < 5 km from the Navrongo town, and /or access to developed roads(yes/no]) were included alongside time “step” functions (representing follow-up years 0—1, 1—3 and 3 +) to evaluate time varying values and to evaluate whether these variables influenced findings (Zhang et al., 2018). In addition to all-cause mortality, Cox models were developed to evaluate the association between air pollution exposure and Acute Respiratory Infection (ARI) mortality – based on a-priori expectations that air pollution exposure may be relevant for this outcome (Odo et al., 2022).

Finally, Kaplan-Meier survival curves were employed to visualize the survival experience of children based on sociodemographic and background characteristics. Results of the Cox proportional hazards regression are presented as hazards ratios (HR) with 95 % confidence intervals. Statistical significance of all inferential statistics was determined at a two-sided $p < 0.05$. All statistical analyses were performed using R software version 4.3.0 (2023–04-21) and RStudio (2023.09.1) (Odo et al., 2022). Some of the packages used included survival, ggplot2, survminer, glmnet, and dplyr (R Core Team. A language and environment for statistical computing. Vienna: https://www.R-project.org/;, 2022).

3. Results

3.1. Basic characteristics

There were 48,352 live births between the years 2007 and 2017. The majority (69 %) of the mothers were aged 20 to 34 years and predominantly (84.8 %) lived in rural areas. Unclean fuels were used by the majority of the population for cooking (84.5 %). The overall follow-up period was 150,099 person-years with a median follow-up period of 3.35 person-years. During the study period 1,872 deaths occurred, corresponding to a mortality rate of 38.7 deaths per 1,000 live births. Neonatal, infant and child deaths accounted for 30.5 %, 33.1 % and 36.4 % of deaths respectively. There was a significant difference in mortality rates between the various age groups ($p < 0.001$) and sex of the child, with more males likely to die compared to females (54 % versus 46 %; $p < 0.001$). Rural residence (88 %), poor household (71.4 %), and unclean household cooking fuel (89.6 %) were associated with higher proportions of deaths (Table 1).

3.2. $PM_{2.5}$ levels in the study area over the study period

The assigned early-life exposure of the study population to $PM_{2.5}$ varied from 20.9 to 69.7 μg/m3, with a mean exposure of 39 μg/m^3. In the alternative model where dust and sea-salt were algorithmically removed, $PM_{2.5}$ varied from 1.43 to 13.63 μg/m3 with a mean of 7.53 μg/m3. Supplementary Fig. 1 visually displays the distribution of $PM_{2.5}$ estimates, along with the air quality guidelines recommended by the World Health Organization (WHO). Fig. 2 shows mean $PM_{2.5}$ levels and U5M rate per 1000 live births. During the observation period, U5M declined from 68.4 deaths per 1000 live births in 2007 to 12.7 in 2017. By contrast, average $PM_{2.5}$ levels have shown no clear trends except the last 2 years posing the highest annual averages.

Supplementary Table S1 presents data on $PM_{2.5}$ levels at birth against the place of residence and mortality outcomes. $PM_{2.5}$ at birth was observed to be higher for births in urban areas (41.2 ± 8.8 μg/m^3) compared to rural areas (38.7 ± 8.2 μg/m^3). Average pollution varied across the different geographical zones with the Central, predominantly urban, zone, recording the highest (41.7 ± 8.8 μg/m^3) $PM_{2.5}$ concentration.

3.3. Cause of death in the Navrongo HDSS

Out of the total 1829 deaths reported, cause of death was determined for 70 %. For the remaining 30 %, the cause could not be established either due to insufficient information collected for coding or the complexity involved in identifying the specific cause of death. Table S4 shows the top 10 causes of deaths in the study area by age group and proportion of the total deaths. Malaria (22.1 %) and sepsis (13.8 %) were the leading causes of death. Mortality from respiratory infections, birth trauma, prematurity and low birth weight followed with death rates of 5.3 %, 4.5 % and 3.4 % respectively. The average $PM_{2.5}$ exposure at birth was highest for birth asphyxia and birth trauma (39.5 μg/m^3) and acute respiratory infection with 39.1 μg/m^3 (Table S2).

Table 1
Individual, maternal, and household characteristics of children under-five years in the between 2007 and 2017.

Factors	Level	Total N = 48352	Deaths N = 1872	X^2 statistics p-value
Child's age	0.27 days-Neonates	978 (2.0)	573 (30.6)	<0.01
	1–11 months-Infant	7647 (17.8)	616 (32.9)	
	1–4 years-Child	39,727 (82.2)	683 (36.5)	
Sex of child	Female	24,065 (49.8)	858 (45.8)	<0.01
	Male	24,287 (50.2)	1014 (54.2)	
Mother's Age	≤19	5,919 (12.2)	243 (13.0)	<0.01
	20–34	33.295 (68.9)	1170 (62.5)	
	35 or more	9,138 (18.9)	459 (24.5)	
Mothers' religion	African Traditional *	18,082 (37.4)	823 (44.0)	<0.01
	Other Christianity	11,752 (24.3)	429 (22.9)	
	Catholic	10,030 (20.7)	348 (18.6)	
	Islam	3,092 (6.4)	128 (6.8)	
	Other	103 (0.2)	2 (0.1)	
	Missing	5293 (11.0)	142 (7.6)	
Residence of mother	Urban	7,315 (15.1)	221 (11.8)	<0.01
	Rural	41,037 (84.9)	1651 (88.2)	
Household socioeconomic status*	Poorest	12,177 (25.2)	591 (31.6)	<0.01
	Poorer	9,889 (20.5)	412 (22.0)	
	Poor	8,056 (16.7)	334 (17.8)	
	Less poor	8,050 (16.7)	268 (14.3)	
	Least poor	4,880 (10.1)	125 (6.7)	
	Missing	5300 (11.0)	142 (7.6)	
Maternal education level	No education	10,246 (21.2)	549 (29.3)	<0.01
	Primary	14,245 (29.5)	596 (31.8)	
	JSS/Middle	12,125 (25.1)	435 (23.2)	
	Secondary	12,125 (12.6)	169 (9.0)	
	Tertiary	2,944 (6.1)	60 (3.2)	
	Missing	2,711 (5.6)	63 (3.4)	
Birthplace	Health Facility	32,554 (67.3)	1136 (60.7)	<0.01
	Home/ Somewhere	8,515 (17.6)	577 (30.8)	
	Missing	7,283 (15.1)	159 (8.5)	
Zones	Central	3,824 (7.9)	132 (7.1)	0.04
	North	10,974 (22.7)	414 (22.1)	
	South	15,282 (31.6)	567 (30.3)	
	East	8,848 (18.3)	390 (20.8)	
	West	9,423 (19.5)	369 (19.7)	

(*continued on next page*)

Table 1 (*continued*)

Factors	Level	Total N = 48352	Deaths N = 1872	X^2 statistics p-value
	Missing	1 (0.0)	0 (0.0)	
Cooking Fuel	Clean	2,130 (4.4)	47 (2.5)	<0.01
	Unclean	40,844 (84.5)	1678 (89.6)	
	Other	83 (0.1)	5 (0.3)	
	Missing	5,295 (11.0)	142 (7.6)	
Year of Birth	2007	4547	131	
	2008	4225	213	
	2009	4295	219	
	2010	4424	209	
	2011	4484	203	
	2012	4507	194	
	2013	4388	141	
	2014	4581	124	
	2015	4380	192	
	2016	4274	121	
	2017	4247	125	

*Derived through principal component analysis (PCA). Estimated using household assets.

* traditional religion“ or African Traditional religion refers to indigenous or local belief systems and practices that have been culturally and historically rooted. It often involves customs, rituals, and spiritual beliefs that are passed down through generations within a community or region.

Data presented as n (%); p-value computed from Pearson’s Chi Squared test and represents differences between the groups.

4. Association of early-life PM2.5, fuel use and socio-demographic characteristics with U5M (all-cause-mortality) in the NHDSS

Cox proportional hazards regression analysis showed early-life $PM_{2.5}$ levels were not significantly associated with U5M. The unadjusted hazard ratio (HR) for early-life $PM_{2.5}$ levels were 0.99 (95 % confidence interval [CI]: 0.99,1.00) for a single unit increment in $PM_{2.5}$, and the adjusted HR was 1.00 [0.99,1.00]. When specifically examining $PM_{2.5}$ with dust and sea salt removed, a negative association with $PM_{2.5}$ was observed (0.91 [0.86, 0.95]) (see supplementary Table S3).

U5M showed a significant positive association with the cooking fuel type used by households. Children from households that used unclean cooking fuels had a 73 % higher risk of death compared to children from households that used clean cooking fuels (adjusted HR 1.73; 95 % CI [1.29–2.33]) as indicated in Table 2. In sensitivity analysis (Table S4) where the role of maternal education, residence, and wealth index were considered. A positive relationship for solid fuel use and mortality was observed, albeit closer to 1 than the main models (HR: 1.40, 95 % CI: 1.02, 1.92). The previously observed null relationship for $PM_{2.5}$ remained for this sensitivity analysis.

Males had a 15 % higher risk of U5M (aHR, 1.15; 95 % CI: 1.05–1.27). Mother’s age between 20 to 34 years had a non-significantly lower risk of U5M compared to ages less than 19 years (aHR: 0.88 [0.76, 1.02]; p = 0.08). Conversely, children born to mothers aged 35 + had a 16 % increased risk of death (also non-significant) compared to ages less than 19 (aHR 1.16 [0.98, 1.36]).

4.1. *Survival probabilities of U5Ms in the NHDSS*

Kaplan-Meier survival curves each representing a different variable were generated to analyze the survival probabilities of the study population based on various factors (Fig. 4). Being female, born to mothers aged 20–34 years, and use of clean fuel was associated with higher survival probabilities.

5. Discussion

The current study examined ambient air pollution in relation to U5M and other household characteristics in the Navrongo Health and Demographic Surveillance System (NHDSS) area from 2007 to 2017. Over the course of the 11-year study period we observed a decline in the under-five mortality rate from 68.4 to 12.7 per 1000 live births. This represents a substantial improvement in under-5 mortality towards meeting the Sustainable Development Goal (SDG) target of reducing under-5 deaths to below 25 per 1000 live births by 2030 (SDG, 2022).

In our analysis, early-life $PM_{2.5}$ exposure did not show a significant association with U5M after adjusting for other factors. In a study of data from 43 low-and-middle-income countries, Goyal et al (2019) also reported no overall association between ambient air pollution and child mortality at either the neonatal (odds ration = 1.08, 95 % [CI]: 0.95, 1.23), post-natal (0.89 [0.76, 1.05]) or infant age (0.99 [0.89, 1.12]) (Goyal et al., 2019). However, after disaggregating out naturally occurring dust and sea-salt, they observed a positive association between $PM_{2.5}$ and neonatal death (1.22 [1.11, 1.35]) They therefore concluded that the mechanism responsible for the association between ambient air-pollution exposure and mortality may depend on the composition and toxicity of particulate matter. Similarly, Lien et al (2019) and Novack (2020) stated that it is more common to identify effects from anthropogenic pollution sources than naturally occurring pollution (Lien et al., 2019; Novack et al., 2020). This might explain why a null relationship overall was observed here (alongside a negative relationship for $PM_{2.5}$ with dust and sea salt algorithmically removed), as although the levels of $PM_{2.5}$ observed are well in excess of the WHO recommended levels, there appears to be a large contribution of non-anthropogenic sources (Moro et al., 2022; Moro, 2020).

In addition to examining ambient air pollution, we also examined household pollution via the proxy of household fuel use. In doing so we observed a significant association between household cooking fuel use and U5M – where children from households using unclean cooking fuels had a 73 % higher risk of death compared to those from households using clean cooking fuels. It is important to highlight that this study did not collect data on household kitchen types. However most households in the area have semi-closed kitchens that are located within the household (Dickinson et al., 2018; Coffey et al., 2019). Cooking behaviour also varies by season with all cooking done indoors during the raining and harmattan seasons (Dickinson et al., 2015). Despite this, these findings aligns with previous research that has consistently demonstrated adverse effects of indoor air pollution resulting from the use of solid fuels for cooking on child health outcomes (Adjei-Mantey and Takeuchi, 2021). A systematic review and *meta*-analysis conducted by Amegah et al (2017) including 15 cohort studies in low- and middle-income countries found that exposure to solid fuel use for cooking was associated with a 36 % increase in the risk of child mortality (Amegah et al., 2017). Mishra et al. (2003) observed that children living in households using biomass fuels in rural Nepal had a higher risk of mortality compared to those using cleaner fuels, highlighting the importance of transitioning to clean cooking technologies to reduce child mortality in resource-constrained settings (Mishra, 2003) Similarly, Balakrishnan et al. (2019) demonstrated a significant association between exposure to solid fuels for cooking and a higher risk of child mortality, particularly from respiratory and infectious diseases in a large-scale study in India, involving over 259,000 households (Balakrishnan et al., 2013). With 84.5 % of households in the Navrongo study area using unclean cooking fuels over biomass stoves, these findings emphasize the urgent need for interventions to mitigate household air pollution and improve child health outcomes. In addition, our study found that children in rural areas had a higher risk of mortality than people in the urban areas. This may be reflective of an increased biomass usage in rural settings or the better availability of health and social interventions in the Navrongo urban area (R Core Team. A language and environment for statistical computing. Vienna: https://www.R-project.

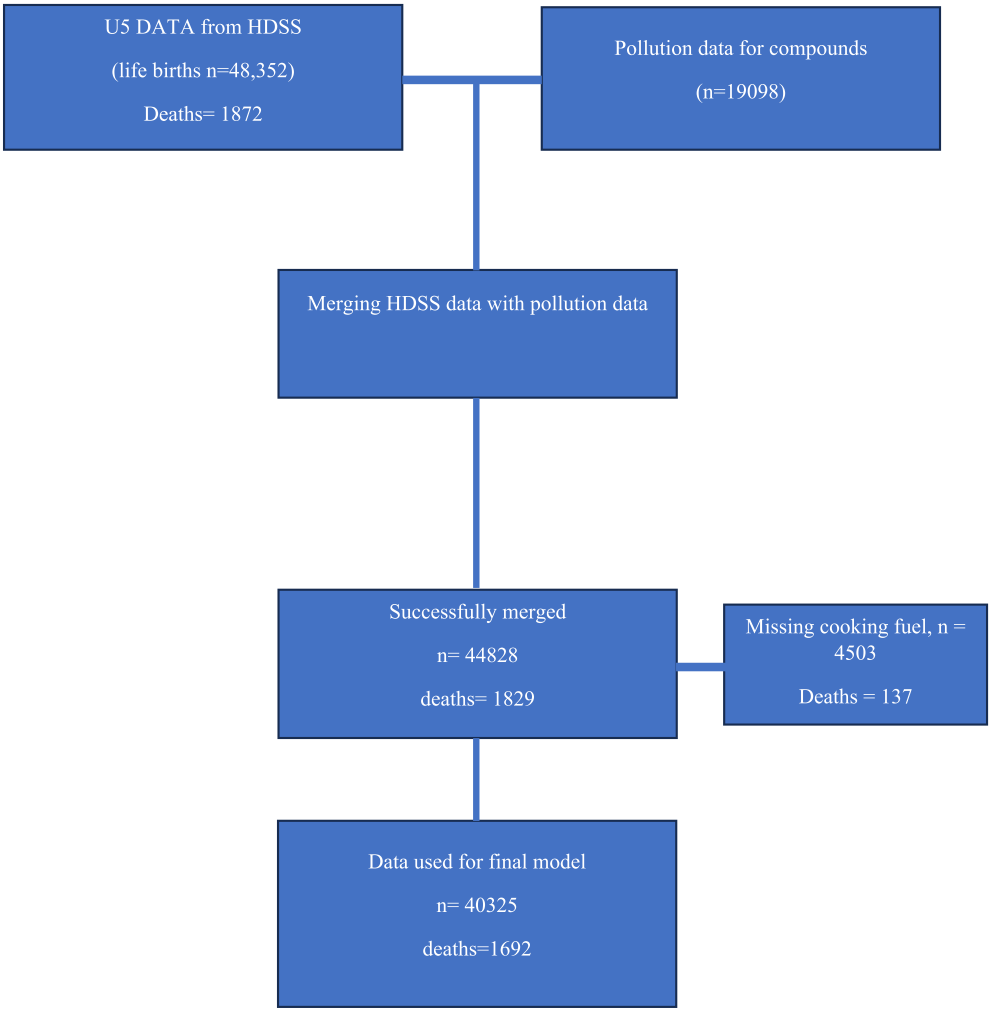

Fig. 2. Subject selection flow chart.

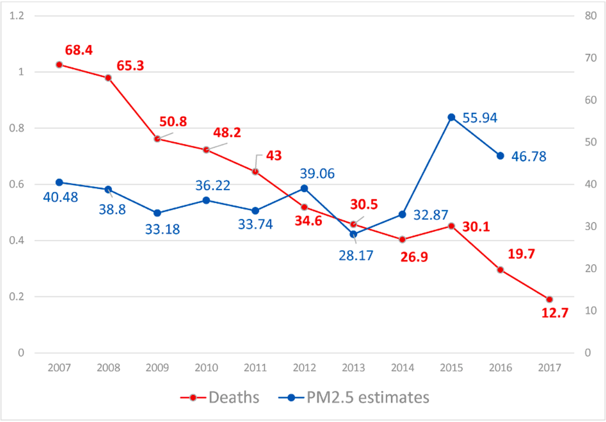

Fig. 3. Annual mean $PM_{2.5}$ (μg/m^3) levels and deaths rate per 1000 live births in the Navrongo Heath and Demographic Surveillance Site 2007–2017.

org/;, 2022; SDG, 2022).

In addition to all-cause mortality, we a-priori attempted to evaluate the role of ambient air pollution and ARI mortality. Dherani et al (2008) in their synthesis of evidence from 31 studies observed that the use of solid fuels was significantly associated with elevated risk of ARIs in children (Dherani et al., 2008) While we observed a high average early-life $PM_{2.5}$ exposure (39.1 μg/m3) among those who died of ARI, this did

Table 2
Hazard Ratios (HR) of early life exposure to $PM_{2.5}$, cooking fuel, socio-demographic characteristics, and all-cause mortality, NHDSS 2007–2017.

Variable	Unadjusted HR (95 %CI)	Adjusted HR for $PM_{2.5}$ (95 %CI)	Adjusted HR for cooking fuel (95 % CI)	Adjusted for Fuel and $PM_{2.5}$ (95 %CI)	P-value
Early-life $PM_{2.5}$ levels	0.99 (0.99–1.00)	0.99 (0.99–1)	–	1.0 (0.99–1.00)	0.64
Cooking		–			
fuel use	Ref1.76		Ref1.73	Ref1.73	
Clean	(1.31–2.37)		(1.29–2.34)	(1.29–2.33)	<0.01
Unclean					
Sex					
Female	Ref1.16	1.16	1.15	Ref1.15	
Male	(1.06–1.27)	(1.06–1.27)	(1.05–1.27)	(1.05–1.27)	<0.01
Mothers					
age	Ref0.84	0.84	0.88	Ref0.88	
Less 19	(0.73–0.97)	(0.73–0.97)	(0.76–1.01)	(0.76–1.02)	0.08
20–34	1.13	1.13	1.16	1.16	0.08
35+	(0.96–1.32)	(0.96–1.32)	(0.98–1.36)	(0.98–1.36)	

n = 40325, number of events = 1692 (4503 observations deleted due to missingness); CI, confidence intervals; HR, Hazards Ratios.

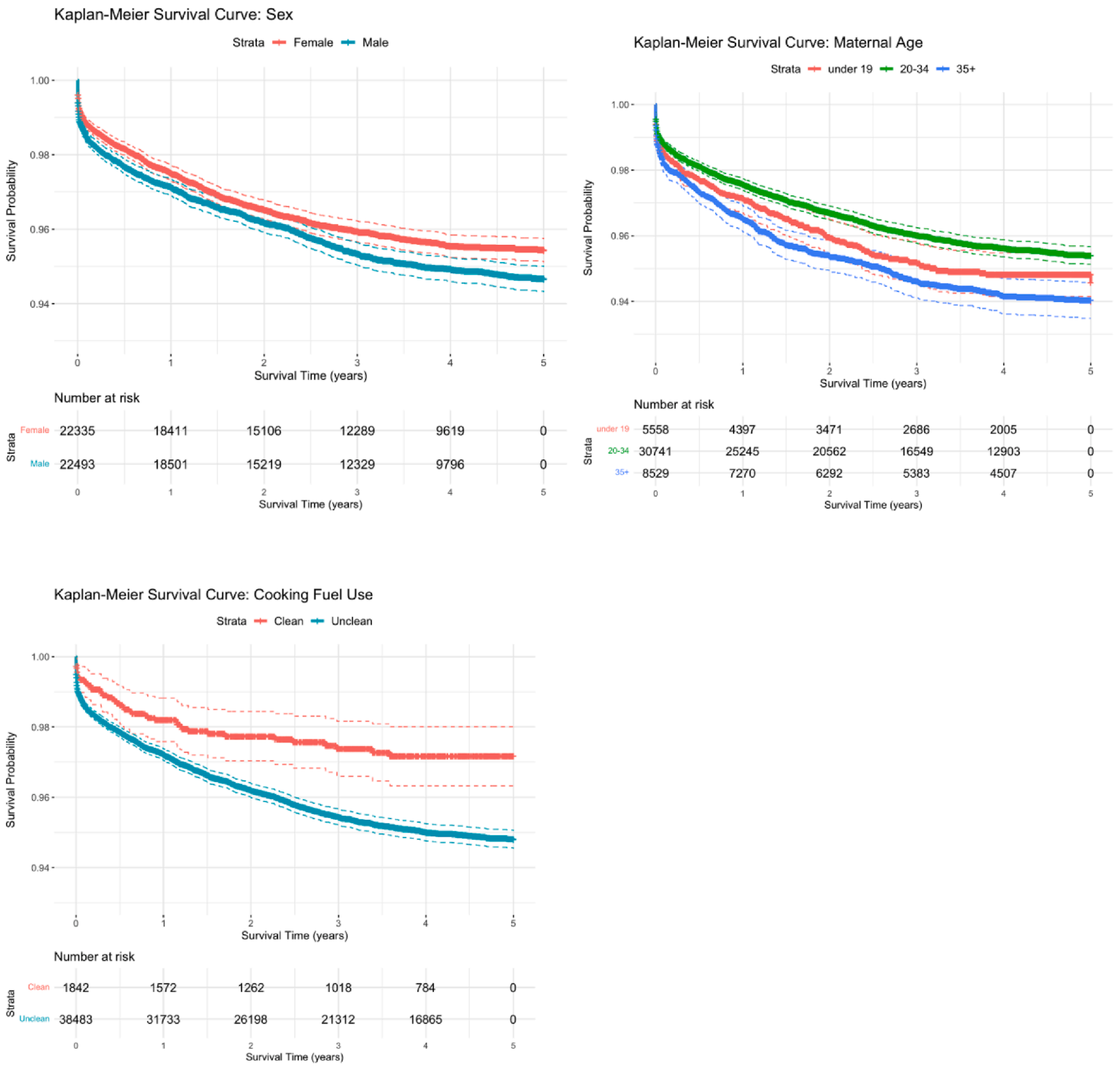

Fig. 4. Survival Probabilities in the Study Population: A Kaplan-Meier Analysis of Factors Influencing Survival.

not equate to an increased risk of death in our Cox Hazard models. Further, while an HR of 1.08 for the use of unclean cooking fuel was observed, it did not attain statistical significance (95 % CI: 0.39, 2.94). Given the small number of cases observed (n = 93) it is possible that the current study was underpowered to detect any true effect.

5.1. Strengths and limitations

Integration within the Navrongo Health and Demographic Surveillance System (NHDDS) represents a notable strength of the current study, as it provides a rich and extensive dataset spanning three decades (1993–2023). The NHDDS consistently surveyed the study area's population, allowing us to gather robust health data and ascertain the causes of deaths through the reliable VA (verbal autopsy) system. This long-term surveillance system provided valuable insights into under-five mortality trends, enabling us to observe a substantial decline in mortality rates over the 11-year study period, moving towards the achievement of the Sustainable Development Goal (SDG) target. Additionally, the well-identified residential locations and well-defined participant covariates added to the study's strength, providing a solid foundation for our analyses and interpretation of results.

The use of globally validated information on $PM_{2.5}$ represents another major strength, allowing an analysis of a region without widespread pollution monitoring information. However, the pollution models utilized relied on ground-based data for validation, which might be less prevalent in African regions. Models were also unable to fully consider residential cooking, which is a significant contributor to air pollution exposure and health (as observed within the current study). The high levels of non-anthropogenic pollution that the NHDSS population was exposed to during the study period, largely influenced by the harmattan dry winds, represents another challenge (Lyngsie et al., 2011). These extreme levels of "natural" pollution might have affected the observed associations between ambient air pollution and mortality outcomes. This is potentially reflected when, after adjusting for $PM_{2.5}$ with dust & sea-salt algorithmically removed, the association between household fuel use and under 5 mortality remains positive but becomes non-significant.

The current study was also limited by the lack of data on secondary fuel use and stove stacking, which is a common phenomenon in the study area. This additional information would have provided a more comprehensive understanding of the households' exposure to different cooking fuels. Additionally, potential confounding factors such as nutritional status; particularly considering the pronounced seasonal variations in nutritional status during the dry season, lifestyle habits (e.g., smoking status of mothers) and genetic factors (For instance, polymorphisms in genes related to antioxidant defense mechanisms e.g., glutathione S-transferase genes or inflammatory responses e.g., interleukin-6) that may influence the relationship between early life PM exposure and mortality were not available in the HDSS data. Accounting for these confounders could have provided a more nuanced analysis of the associations observed. Additionally, by only including live births in the current study, any potential association between environmental exposures and miscarriage or still-birth has not been evaluated – raising the possibility of a "live birth" bias. Finally, the presence of unknown causes of death in the data also posed a limitation, as it hindered a more detailed examination of individual causes of death.

6. Conclusion

In the current study, the under-five mortality rates in the Navrongo area have notably declined over an 11-year period. While early-life $PM_{2.5}$ exposure did not show a significant association with under-five mortality, sex of a child, maternal age and unclean cooking fuel use are predictors of under-five mortality in the study area. Addressing household air pollution through the adoption of clean cooking technologies and targeted interventions remains a crucial public health priority to improve child health outcomes and accelerate progress towards the Sustainable Development Goals target.

Data sharing.

Navrongo HDSS data can be obtained from the institution through a reasonable request to the director (www.navrongo-hrc.org). Specific data for this manuscript can be obtained from the corresponding author upon reasonable request.

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CRediT authorship contribution statement

Ali Moro: Writing – original draft, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Engelbert A. Nonterah:** Writing – review & editing, Supervision, Conceptualization. **Kerstin Klipstein-Grobusch:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Samuel Oladokun:** Data curation. **Paul Welaga:** Writing – review & editing, Data curation. **Patrick O. Ansah:** Supervision, Funding acquisition. **Perry Hystad:** Software, Data curation. **Roel Vermeulen:** Writing – review & editing, Supervision, Investigation, Funding acquisition. **Abraham R. Oduro:** Supervision, Funding acquisition. **George Downward:** Writing – review & editing, Supervision, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: [AM is supported by the Global Health Support Program of the University Medical Center Utrecht (UMCU), University of Utrecht, the Netherlands. All other authors declare no competing interests].

Data availability

Data will be made available on request.

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Research in context.

Evidence before this study.

Prior to this study, existing research had already established a compelling link between ambient air pollution, household fuel use, and child mortality, particularly in low- and middle-income countries (LMICs). Numerous studies had documented the adverse health effects of exposure to fine particulate matter (PM2.5) on respiratory health, especially in early childhood. Additionally, investigations into household characteristics, including cooking fuel types, had consistently shown that the use of unclean fuels posed a significant risk to household air quality and subsequently, child health. However, much of this research was often conducted in diverse contexts, making it essential to examine these associations within specific regions to understand their nuances and implications for targeted interventions. These studies generally had smaller sample sizes and were restricted to patient populations. Literature on individuals on continues surveillance in SSA was not found.

Added value of this study.

This study significantly advances our understanding of the interplay between early-life ambient air pollution, household fuel use, and under-5 mortality in the Navrongo Health and Demographic Surveillance Site in northern Ghana. By focusing on this specific region, the research provides crucial contextual insights that may not have been fully captured in broader global studies. The inclusion of a comprehensive health and demographic surveillance system further strengthens the study's methodology, allowing for a more detailed examination of the population dynamics and health trends in the area. Moreover, the study's specific findings regarding the 24 % higher risk of mortality in households using unclean cooking fuels highlight the urgent need for targeted interventions to improve household air quality and mitigate associated health risks in this vulnerable population.

Implications of all the available evidence.

The collective evidence from this study and existing research underscores the pressing need for concerted efforts to address air quality and household fuel use, particularly in LMICs. It reinforces the imperative for policies and interventions aimed at reducing ambient air pollution, which continues to be a critical public health issue worldwide. The findings emphasize the importance of transitioning to cleaner cooking technologies, not only to improve household air quality but also to significantly reduce the risk of child mortality. Additionally, the study's insights into the specific challenges faced by regions like northern Ghana serve as a call to action for targeted public health initiatives in areas with high levels of air pollution and unclean fuel use. Overall, the available evidence highlights the potential for substantial gains in child health and well-being through focused interventions addressing environmental determinants of health.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2024.108693.

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