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Exposure to Outdoor Particles ($PM_{2.5}$) and Associated Child Morbidity and Mortality in Socially Deprived Neighborhoods of Nairobi, Kenya

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Abstract: Exposure to air pollution is associated with adverse health outcomes. However, the health burden related to ambient outdoor air pollution in sub-Saharan Africa remains unclear. This study examined the relationship between exposure to outdoor air pollution and child health in urban slums of Nairobi, Kenya. We conducted a semi-ecological study among children under 5 years of age from two slum areas and exposure measurements of particulate matter ($PM_{2.5}$) at the village level were aligned to data from a retrospective cohort study design. We used logistic and Poisson regression models to ascertain the associations between $PM_{2.5}$ exposure level and child morbidity and mortality. Compared to those in low-pollution areas ($PM_{2.5} < 25\ \mu g/m^3$), children in high-pollution areas ($PM_{2.5} \geq 25\ \mu g/m^3$) were at significantly higher risk for morbidity in general (odds ratio (OR) = 1.25, 95% confidence interval (CI): 1.11–1.41) and, specifically, cough (OR = 1.38, 95% CI: 1.20–1.48). Exposure to high levels of pollution was associated with a high child mortality rate from all causes (IRR = 1.22, 95% CI: 1.08–1.39) and respiratory causes (IRR = 1.12, 95% CI: 0.88–1.42). The findings indicate that there are associated adverse health outcomes with air pollution in urban slums. Further research on air pollution health impact assessments in similar urban areas is required.

Keywords: air pollution; child health; child morbidity; child mortality; particulate matter; urban poor

1. Introduction

A larger burden of air pollution is experienced in low- and middle-income countries (LMICs) [1] and little evidence exists from this part of the world [2]. In LMICs, the growth of socially deprived informal settlements or urban slums exacerbates the problem of urban air pollution exposure. These settlements are characterized by exposure sources, such as dust and smoke from fuel combustion, combined with exposures sources, such as burning of waste, vehicle exhaust, and industrial pollution, potentially causing a double burden of exposure to air pollutants [3]. Household and ambient air pollution often coexist and hence should be considered together [1]. It is well established that the ambient levels of air pollution in a region can have an impact on the health status of its population [4–7]. Air pollution levels should therefore be taken into account when considering the wider determinants to public health and the impacts that changes in air pollution might have on population health [8].

Long-term exposure and short-term "spikes" in local air pollution levels can affect population health [5,7]. More specifically, children bear a high risk of pollution during the early stages of life even at low levels of exposures to pollutants, and the health effects can be carried across their lifespan [2]. The burden is also disproportionately higher in urban areas. A study on the effects of air pollution in Delhi, India identified a significantly higher prevalence of respiratory symptoms in urban areas compared to rural counterparts [9].

Air pollution remains an under-recognized environmental health risk in LMICs as compared to some high income countries where policies to control air pollution have been put in place [10]. Many LMICs are experiencing high rates of urbanisation and industrialisation which result in a rise in ambient air pollution levels, particularly in urban areas [4]. Globally, it has been estimated that 4.2 million premature deaths in 2016 could be attributed to ambient air pollution [10]. However, health effects of ambient air pollution remain relatively understudied in LMICs, mainly due to the limited infrastructure and policies for undertaking the measurement of air pollution on a continuous basis [11,12]. A recent study combined household survey-based data and satellite-based estimates of exposure to ambient respirable particulate matter ($PM_{2.5}$) and estimated the impact of air quality on mortality rates among infants across sub-Saharan Africa [2]. In Africa, a few exposure studies have been conducted in Ghana [13,14], Kenya [15–19], Tanzania [20], Egypt [21], and Burkina Faso [22], but these have been constrained to look at specific parts of the city for shorter periods of time and no health outcome data was available for analysis. A recent study in two informal settlements of Nairobi, Kenya revealed alarming air pollution levels of outdoor particulate matter [23]. With observed high levels of air pollution in urban areas, studies aiming to establish a relationship between ambient air quality and health are necessary to provide information on the disease burden associated with exposure to air pollution, particularly among children.

Children are more susceptible to the effects of exposure to air pollution, with an increase in the risk of acute respiratory infections, for a number of reasons [24,25]. First, the epithelial linings of children's lungs that are not fully developed offer greater permeability for pollutants [26]; second, their immune systems are not fully developed, limiting the body's defense against infection [27]; and third, children have higher respiration rates and larger lung surface area relative to body weight compared to adults [28]. Compromised pulmonary functions triggered by exposure to air pollution leads to acute respiratory symptoms. In addition, exposure to air pollution can have longer-term health effects resulting in mortality [29]. Studies have shown significant associations between exposure to particulate matter and respiratory morbidity among children [30–32]. A recent study indicated a biological linkage between air pollution exposure and diarrhea [2]. The impacts of air pollution on children health is higher in urban slum areas compared to non-slum areas [12]. This indicates that slum populations often face the greatest health burden associated with exposure to air pollution.

This paper examines the associations of outdoor air quality, as measured by $PM_{2.5}$, on children's health in two urban slum areas of Nairobi. Using a semi-ecological study design, we utilised the Nairobi Urban Health and Demographic Surveillance System (NUHDSS) platform to provide information on morbidity and mortality at the individual level and measured air pollution concentrations at the village level.

2. Methods

2.1. Study Design and Data

This paper builds on the air pollution exposure assessment study conducted in two slums of Korogocho and Viwandani in Nairobi, Kenya. The two study areas are part of the NUHDSS run by the African Population and Health Research Center (APHRC) since 2003. The NUHDSS and two nested studies—the Maternal and Child Health (MCH) project and the INDEPTH (International Network for the Demographic Evaluation of Populations and Their Health) Vaccination Project (IVP))—were the sources of data on mortality and morbidity.

This study aligned a semi-ecological exposure measurement at the village level of $PM_{2.5}$ to a retrospective cohort study design. The health outcomes and covariates were measured at the individual level and air pollution exposure levels were based on aggregated measures at the village level, for a total of eight villages in Korogocho and six villages in Viwandani. A similar approach has been used in various studies [33,34] to examine the relationship between air pollution and adverse health outcomes.

The NUHDSS records demographic events (births, deaths, and migration) every 4 months, providing data on individual residents. As of the end of 2013, a total of 63,484 individuals from 25,474 households were under surveillance. The NUHDSS also integrates the Verbal Autopsy (VA) process for establishing a probable cause of death (COD), which was the source of mortality outcomes in this study. The VA interviews are conducted using a standard VA questionnaire developed in conjunction with other INDEPTH sites and has two versions: one for deaths of children less than 5 years of age and another for deaths of persons 5 years and older. The detailed description of the VA process is provided elsewhere [35].

Child morbidity data for children under five years of age for this study were obtained from nested studies within the NUHDSS, including the Maternal and Child Health (MCH) study and the INDEPTH Vaccination Project (IVP). The MCH study, conducted from 2007 to 2010, recruited cohorts of mother–child pairs and followed them up every 4 months. The study included a mother–child pair if the mother resided in the slum when pregnant and if the child was 6 months old or younger at the time of recruitment. During recruitment sessions, follow-up interviews of existing earlier cohorts were also conducted. The IVP succeeded the MCH project in 2011, taking over the MCH cohorts of children and recruiting all children born after recruitment until the MCH project ended. Therefore, both MCH and IVP projects resulted in a cohort of children recruited from 2007 to 2013 with similar procedures and questionnaires. At every survey, information on whether the child had any illness in the past 2 weeks was collected. For those who reported illness, the type of symptoms—including diarrhea, fever, cough, rapid cough, and convulsion—was determined. In this study, we analysed morbidity as an outcome, including diarrhea and also excluding diarrhea, and further analysed cough separately. We performed analyses including and excluded diarrhea to assess the linkage of diarrhea to the exposure to ambient fine particulate matter.

The household wealth index was calculated based on household amenities and possessions using principle component analysis (PCA) [36]. The list of household possessions, amenities, and livestock ownership is provided in Table A1. The index was then grouped into tertiles (poorest, poor, and least poor).

2.2. Air Pollution Exposure Assessment

Air pollution data were obtained from a continuous real-time sampling study of particulate matter with an aerodynamic diameter of 2.5 microns or less ($PM_{2.5}$). The measurements were conducted from February to October 2013 with a total of 85 sampling days in Korogocho and 121 sampling days in Viwandani. Air pollution measurements, time, date, and geographic coordinates of the sampling points were recorded. The description of the design and observations from the measurement and processing of data is detailed elsewhere [23]. The estimated $PM_{2.5}$ concentrations were averaged at the enumeration area (EA) level and then the EA average $PM_{2.5}$ concentrations were assigned to each household/individual within each EA. The EA varied in size and on average each EA represented approximately 100 households. The overall median $PM_{2.5}$ concentration was 53.9 $\mu g/m^3$ at the EA level with an interquartile range of (16.1 to 66.0 $\mu g/m^3$). The lowest observed $PM_{2.5}$ level was 8.4 $\mu g/m^3$ and the highest was 483.6 $\mu g/m^3$. The exposure level was further categorized to either below or at/above 25 $\mu g/m^3$. The choice of the cutoff was based on the 24-h World Health Organization (WHO) recommended limit [37], although the measurements were not done for a complete 24 h for this study. However, the measurements are assumed to provide a conservative estimate for 24-h comparison.

2.3. Statistical Analysis

The analysis for both morbidity and mortality was performed for children up to the age of 5 years. Therefore, children were included in the analysis at different times as long as they were not more than 5 years at that time point. We examined the association between air pollution and morbidity using prevalence and episode analyses. A multilevel analysis approach with logistic regression for binary outcome (prevalence analysis) and Poisson regression for count observations (episode analysis) were used. A multilevel approach was used because traditional regression assumes the units of analysis as independent observations. Failing to recognize the hierarchical structures present in the data results in underestimation of standard errors of coefficients, leading to an overstatement of statistical significance [38]. For prevalence and episode analysis at the individual level, the three-level models were used to account for the fact that observations/events were nested within children and children were nested within households, while a two-level model was used for episode analysis at the household level.

The period prevalence (i.e., entire study period) analysis for binary outcome was conducted using three-level logistic regression at individual, household, and village levels. The episode analysis was performed using two-level Poisson regression at individual and household levels. The episode analysis at the individual level used the number of morbidity occurrences within an individual during the entire follow up period as an outcome, while at household level, we used the number of morbidity occurrences for all children within a household. The analysis of morbidity was conducted separately for cough and for occurrence of either cough, fever, or convulsion including and excluding diarrhea.

Mortality analysis in relation to air pollution exposure level was conducted for all-cause and respiratory-related mortality. Data on all-cause and respiratory-related mortality were aggregated per person-years of observation by sex, age group, and wealth index. Person-time was calculated using residency status so that residents contributed to person-time as long as they had been living in the NUHDSS area since 2003. After aggregating the person-time by child characteristics, a Poisson regression was used to estimate and compare the incidence (mortality) risk ratio (IRR) for all-cause and respiratory-related mortality adjusting for household wealth index, sex, and age of the child. All analyses were performed using Stata Statistical Software Release 13 (StataCorp LP, College Station, TX, USA).

3. Results

3.1. Study Cohort Descriptions

A cohort of 4529 children aged below 5 years were followed up during the period 2012–2013 and included in the morbidity analysis, and a total of 21,641 children under 5 years were observed for the period 2003–2013, forming a cohort for mortality analysis. We used a longer period of follow up for mortality analysis given the lower mortality incidence compared to morbidity incidence in the study area. The main characteristics of the two cohorts for both morbidity and mortality analysis are described in Table 1 according to the area level of air pollution exposure (low vs. high). The proportion of participants with missing information on wealth index for the two cohorts was similarly distributed between the two levels of pollution categories.

Although the overall distribution of gender and age class was similar between the exposure categories, people living in areas with high concentrations of $PM_{2.5}$ were more frequently living in poorer households in both cohorts. Among children in the morbidity cohort, about 45% of children in the highly polluted areas lived in poorer households compared to only 25.2% in the less polluted areas. There was a similar distribution for the mortality cohort, where 34.4% of children in the highly polluted areas lived in the poorer households compared to 17% of children in the less polluted areas.

Among the morbidity cohort, a total of 1802 children (39.8%) experienced morbidity with 1454 (80.7%) of them reported to have had cough during 2012–2013. Both morbidity and cough cases were equally distributed by gender: 890 female (49.3%) and 731 female (50.3%) for morbidity and cough, respectively. During the study period (2003–2013), we observed 1330 under 5 years of age all-cause deaths (6.2%), and a total of 357 of these deaths were related to respiratory infection (26.7%). There were a total of 710 deaths from all causes among boys (53.0%), of which 194 deaths were respiratory related (54.2%). Most of deaths occurred within the first 12 months of life; the number and proportion were estimated to be 1103 (82.4%) and 310 (86.6%) for all-cause and respiratory-related causes of death, respectively.

Table 1. Distribution of individual characteristics of the two study cohorts by high and low exposure concentration.

	Morbidity Cohort (2012–2013)						Mortality Cohort (2003–2013)					
	$PM_{2.5}$ < 25 µg/m^3		$PM_{2.5} \geq 25$ µg/m^3		Total		$PM_{2.5}$ < 25 µg/m^3		$PM_{2.5} \geq 25$ µg/m^3		Total	
Gender	n	%	n	%	n	%	n	%	n	%	n	%
Male	798	50.4	1485	50.4	2283	50.4	3937	46.9	6416	48.4	10,353	47.8
Female	785	49.6	1461	49.6	2246	49.6	4456	53.1	6832	51.6	11,288	52.2
Age (months)												
0–11	323	20.4	598	20.3	921	20.3	2330	27.8	3470	26.2	5800	26.8
12–23	411	26.0	704	23.9	1115	24.6	1664	19.8	2434	18.4	4098	18.9
24–35	279	17.6	546	18.5	825	18.2	1102	13.1	1702	12.9	2804	13.0
36–47	301	19.0	595	20.2	896	19.8	786	9.4	1225	9.3	2011	9.3
48–60	269	17.0	503	17.1	772	17.1	2511	29.9	4417	33.3	6928	32.0
Wealth Index												
Poorest	399	25.2	1324	44.9	1723	38.0	1427	17.0	4554	34.4	5981	27.6
Poor	553	34.9	830	28.2	1383	30.5	2586	30.8	3841	29.0	6427	29.7
Least poor	557	35.2	640	21.7	1197	26.4	3450	41.1	3418	25.8	6868	31.7
Missing	74	4.7	152	5.2	226	5.0	930	11.1	1435	10.8	2365	10.9
All-Cause Morbidity												
Yes	550	34.7	1252	42.5	1802	39.8	-	-	-	-	-	-
No	1033	65.3	1694	57.5	2727	61.1	-	-	-	-	-	-
Cough *												
Yes	424	77.1	1030	82.3	1454	80.1	-	-	-	-	-	-
No	126	22.9	222	17.7	348	19.9	-	-	-	-	-	-
All-Cause Mortality												
Yes	-	-	-	-	-	-	473	5.6	857	6.5	1330	6.2
No	-	-	-	-	-	-	7915	94.4	12,396	93.53	20,311	93.8
Respiratory-related mortality **												
Yes	-	-	-	-	-	-	133	28.1	224	26.1	357	26.8
No	-	-	-	-	-	-	340	71.9	633	73.9	973	73.2
Sample (n)	**1583**		**2946**		**4529**		**8353**		**13,288**		**21,641**	

** Sample total based on All-Cause Morbidity cases; ** Sample total is based on All-Cause Mortality cases.*

3.2. Association between Exposure and Child Morbidity

Table 2 presents results assessing relationship between air quality ($PM_{2.5} \geq 25$ µg/m^3) and child morbidity adjusting for gender, age, and wealth status. The detailed results including adjusted factors are provided in the Appendix A (Tables A2–A4). We found a significant association between high exposure level ($PM_{2.5} \geq 25$ µg/m^3) and morbidity considering cough, fever, or convulsion symptoms. A similar relationship with higher risk estimates was observed when considering cough as the only form of morbidity (Table A3). To assess the link between diarrhea and air quality measure, we performed analyses using morbidity including diarrhea. The risk estimates decreased for prevalence analysis at the individual level and episode analysis at the household level, indicating no linkage with diarrhea. However, the risk estimates for episode analysis remained the same after including diarrhea in the definition of morbidity (Table A4). Looking at diarrhea alone (results not shown), we found a significant result for episode analysis at the individual level (i.e., analysis of number of diarrhea episodes at child level). We found a higher prevalence of morbidity (excluding diarrhea) in areas with high $PM_{2.5}$ concentrations. Children in areas with higher exposures were 25% more likely to report morbidity (odds ratio (OR) = 1.25, 95% confidence interval (CI) = 1.11–1.41) after controlling for gender, age of the child, and household wealth index. Morbidity was more often reported among children from poorer households compared to children from less poor households. Less poor households were about 30% less likely to report morbidity (OR = 0.70, 95% CI = 0.60–0.81). The results show that morbidity prevalence was higher among younger children compared to older children, described by a linear age trend. We found no difference in the morbidity prevalence between boys and girls.

Table 2. Adjusted association of air quality (particulate matter ($PM_{2.5}$) > 25 μg/m^3 vs. $PM_{2.5} \leq 25$ μg/m^3) with child morbidity for different analyses.

	Morbidity $^+$			**Morbidity $^{++}$**			**Morbidity $^{+++}$**		
	OR	**95% CI**		**OR**	**95% CI**		**IRR**	**95% CI**	
Individual level analysis—prevalence	1.25	1.11	1.41	1.38	1.20	1.58	1.19	1.07	1.33
Individual level—episode analysis	1.16	1.06	1.28	1.21	1.08	1.35	1.16	1.07	1.25
Household level—episode analysis	1.21	1.11	1.33	1.31	1.18	1.47	1.10	1.04	1.17

$^+$ *Morbidity excluding diarrhea;* $^{++}$ *morbidity defined by cough only;* $^{+++}$ *morbidity including diarrhea. Results were adjusted for sex, age, and household wealth status.*

The results of morbidity (including diarrhea) episodes at the individual level show that children from areas with a high level of pollution had an incidence rate ratio (IRR) of 1.16 (95% CI = 1.06–1.28) times greater than those from areas of low levels of pollution after controlling for sex, age, and wealth index. The results showed a higher incidence rate ratio of morbidity episodes for older children aged 1–4 years compared to children aged below 1 year. High concentration levels of $PM_{2.5}$ were also found to be significantly associated with morbidity episodes at the household level. The results indicate that households in highly polluted areas were 21% more likely to experience morbidity episodes compared to households from less polluted areas (IRR = 1.21, 95% CI = 1.11–1.33).

3.3. Association between Exposure and Child Mortality

A significant relationship between high levels of $PM_{2.5}$ with under 5 years of age all-cause mortality was observed (Table 3). The incidence mortality ratio for children in highly polluted areas was 1.22 compared to children in less polluted areas (95% CI = 1.08–1.39) after adjusting for sex, age, and wealth index. The mortality rate was higher among the poorest households and among children below 1 year of age. However, there was no difference in mortality between boys and girls. The analysis of exposure associations to respiratory-related mortality indicated that children from high exposure areas were 12% more likely to die from respiratory-related infections compared to those from low exposure areas, although the results were not statistically significant (IRR = 1.12, 95% CI = 0.82–1.42).

Table 3. Association between $PM_{2.5}$ and child mortality adjusting for gender, age, and socioeconomic status.

	All-Cause Mortality			**Respiratory-Related Mortality**		
	IRR	**95% CI**		**IRR**	**95% CI**	
Female (vs. Male)	1.02	0.91	1.14	1.01	0.81	1.25
Age Group (ref: 0–11 months)						
12–23 months	0.28	0.24	0.32	0.27	0.21	0.34
24–35 months	0.10	0.08	0.14	0.10	0.07	0.16
36–47 months	0.08	0.06	0.11	0.05	0.03	0.11
48–60 months	0.03	0.02	0.05	0.04	0.02	0.10
Wealth Index (ref: Poorest)						
Poor	0.82	0.70	0.95	0.94	0.69	1.29
Least Poor	0.77	0.66	0.90	0.96	0.70	1.30
Air Quality * ($PM_{2.5}$ > 25 μg/m^3)	1.22	1.08	1.39	1.12	0.88	1.42

* *Poor air quality refers to fine particulate matter ($PM_{2.5}$) $\geq$ 25 μg/m^3.*

4. Discussion

This study assessed the association between exposure to outdoor ambient $PM_{2.5}$ levels and child health among socially deprived urban populations in Nairobi, Kenya. We used a semi-ecological exposure and cohort epidemiological design for children under the age of 5 years from two slum areas of Nairobi. We found significant associations between outdoor fine particulate matter concentrations in the air on respiratory symptoms and all-cause mortality among the study population. Children living in areas with high levels of pollution were at a significantly higher risk for cough and morbidity in general compared to those living in areas with less pollution. We also found high all-cause mortality rates among children living in areas with high levels of pollution. In addition, we found an increased risk of respiratory-related deaths associated to the level of pollution concentration, though the relationship was not statistically significant. We note, however, that the insignificant results for the respiratory-related mortality might be due to the low number of cases for this analysis. Overall, our findings indicate that fine particulate air pollutants contribute significantly to the disease burden for populations residing in the urban slum areas in sub-Saharan Africa. These findings are important in identifying policies and interventions for sustainable health and societal development, and more particularly, regarding efforts towards achieving Sustainable Development Goal 3 of ensuring healthy lives and promoting well-being for those of all ages [39]. Prior to this study, the relationship between health and outdoor air pollutants in the region has not been well researched, particularly in urban informal settlement areas.

Our findings are similar to a study in SSA [2], which showed a significant association level of exposure to $PM_{2.5}$ with child mortality. Studies in China [30] and India [40] have also demonstrated a significant association between child morbidity and level of exposure to particulate matter. Higher prevalence rates of child morbidity were consistently found among children living in areas of high pollution. Incidence of cough, which is a sign of pulmonary irritation that could be caused by exposure to air pollution, was a common child health outcome across these studies in China and India. Our findings reinforce the findings by Ghosh et al. [12], which showed that the burden of air pollution is disproportionately larger on children in slums than other non-slum urban areas. However, our study was not designed to provide a comparison between slum and non-slum areas but provides evidence for the air pollution health-related burden in a population faced with multiple risk factors related to social deprivation. Our finding on the association of exposure to $PM_{2.5}$ with diarrhea is not conclusive, though Heft-Neal et al. [2] found a significant association as evidence of linkage beyond lower respiratory infection (LRI).

Previous studies in Nairobi indicate a high prevalence of respiratory illnesses and asthma among children in slums [41] and acute respiratory infections as the leading contributor of mortality burden among children under 5 years of age [42]. In addition, a seasonal pattern of pneumonia-related mortality for children under 5 years of age was observed in the same population and is thought to be associated with air pollution [43]. A pilot study among children living near the Dandora dumpsite revealed a high incidence of diseases linked to environmental pollution [44]. For example, the study showed that half of the children examined had respiratory ailments and blood lead levels exceeding internationally accepted toxic levels. Our study provides new insights and indicates a health impact from poor ambient air quality as the determinant of poor health outcomes among the slum population. Combining ecologic- and individual-level data in a semi-ecological design as in this study makes it less susceptible to ecological bias, although the implications of aggregating the exposure data across the enumeration area should be carefully examined [45].

The air pollution situation in the study areas is a serious public health problem. In both the study areas, the level of fine particulate matter rises as high as five times the WHO recommended limits [23]. Surprisingly, the community residents do not realize and understand well enough the risks of the pollution levels [46], and most have a "don't care" attitude and responded by saying, "We are used to this" [47].

Our study has a number of limitations. First, a morbidity measure of cough and fever occurrence is indicative of pulmonary stress but is a less perfect measure of air-pollution-related health impacts compared to a lung function test. However, as noted in other reports [40], cough is a much easier symptom of respiratory ailment to monitor; therefore, our study findings are still useful in identifying the immediate effects of exposure to air pollution on children in urban poor population. A second concern stems from the use of exposure assessment data that were based on air pollution measurements during the year 2013, while the outcomes are for cohorts starting in 2003 for mortality and 2012 for morbidity. Therefore, the exposure measurements were conducted after the outcome measurement as opposed to the standard requirement that exposure comes before the outcome. However, our assumption is that the measured exposure contrast between villages has remained similar over the study period. Similar approaches have been used by different studies in Europe. for example, in the Netherlands [11,48,49]. These studies have shown that spatial air pollution contrasts often remained the same for periods up to 10 years, even with a decrease in concentrations over time. Although it may not be case for our study sites, the surveillance data from the NUHDSS shows that the sources and nature of air pollution in these two communities have been unchanged over the past 10 years [50,51]. Further, we did not conduct the exposure measurements for an extended period, which would have allowed us to consider seasonality in this study. Therefore, these limitations of the analysis could lead to residual confounding by poverty and the temporal mismatch between the exposure and health data.

5. Conclusions

In conclusion, we have provided novel evidence on the effects of exposure to ambient air pollution on child health in the urban slum settings of sub-Saharan Africa. The study shows important evidence of higher risk of child mortality in more polluted urban areas in Nairobi. The findings indicate an urgent need to take effective actions to reduce the air pollution levels and improve the situation and health for residents of Nairobi's informal settlements. Our findings provide evidence regarding child health associations to fine particulate matter concentrations that should be seriously considered by professionals and policy-makers when designing policies and strategies to reduce the burden of disease among children in rapidly developing urban areas of Africa.

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Conflicts of Interest: The authors declare that they have no competing interests.

Abbreviations

LMIC	Low and Middle Income Countries
NUHDSS	Nairobi Urban Health Demographic Surveillance System
APHRC	African Population and Health Research Center
ARI	Acute Respiratory Infection
MCH	Maternal and Child Health
IVP	INDEPTH Vaccination Project
VA	Verbal Autopsy

INDEPTH	International Network for the Demographic Evaluation of Populations and Their Health
COD	Cause of Death
PM	Particulate Matter
GPS	Geographic Positioning System
WHO	World Health Organization
PCA	Principle Component Analysis
IRR	Incidence Risk Ratio
OR	Odds Ratio
SES	Socioeconomic Status
CI	Confidence Interval

Appendix A

Table A1. The list of household possessions, amenities, and livestock ownership.

Possessions		Amenities	Livestock
Vehicle	Electric/gas stove	Source of drinking water	Cattle
Motorcycle	Sofa set	Toilet facilities	Goats
Bicycle	Table	Floor, roof, wall materials	Pigs
Refrigerator	Torch	Cooking place	Chicken
Television	Kerosene lamp with glass	Cooking fuel	Donkeys
Radio/stereo	Kerosene stove	Source of lighting	
DVD/VCD/VCR	Wall clock	Garbage disposal	
Sewing machine	Mattress	Dwelling tenure	
Electric iron	Blankets	Room density	
Fan	Bed		
Telephone/mobile phone			

Table A2. Association between $PM_{2.5}$ and child morbidity (excluding diarrhea) adjusting for gender, age, and socioeconomic status.

	Prevalence Analysis			Episode Analysis-Individual			Episode Analysis-Household		
	OR	95% CI		IRR	95% CI		IRR	95% CI	
Female (vs. Male)	0.98	0.87	1.09	0.99	0.91	1.07	0.98	0.90	1.06
Age Group (ref: 0–11 months)									
12–23 months	0.80	0.69	0.92	1.67	1.38	2.02	0.87	0.77	0.97
24–35 months	0.64	0.54	0.75	1.93	1.60	2.33	0.73	0.64	0.82
36–47 months	0.62	0.52	0.73	1.34	1.11	1.63	0.73	0.64	0.83
48–60 months	0.53	0.43	0.65	1.01	0.83	1.24	0.65	0.56	0.76
Wealth Index (ref: Poorest)									
Poor	0.69	0.60	0.79	0.73	0.66	0.81	0.78	0.71	0.87
Least Poor	0.70	0.60	0.81	0.73	0.65	0.81	0.80	0.72	0.89
Air Quality ($PM_{2.5}$ > 25 μg/m^3)	1.25	1.11	1.41	1.16	1.06	1.28	1.21	1.11	1.33

Table A3. Association between $PM_{2.5}$ and child morbidity (cough only) adjusting for gender, age, and socioeconomic status.

	Prevalence Analysis			Episode Analysis-Individual			Episode Analysis-Household		
	OR	95% CI		IRR	95% CI		IRR	95% CI	
Female (vs. Male)	1.02	0.90	1.16	1.02	0.93	1.13	1.02	0.92	1.12
Age Group (ref: 0–11 months)									
12–23 months	0.74	0.63	0.87	1.63	1.31	2.02	0.81	0.71	0.92
24–35 months	0.60	0.50	0.72	1.90	1.53	2.35	0.69	0.60	0.79
36–47 months	0.57	0.47	0.69	1.34	1.07	1.67	0.68	0.59	0.79
48–60 months	0.50	0.40	0.63	0.97	0.77	1.22	0.62	0.52	0.74
Wealth Index (ref: Poorest)									
Poor	0.67	0.57	0.79	0.71	0.63	0.80	0.76	0.68	0.86
Least Poor	0.65	0.54	0.77	0.66	0.58	0.75	0.73	0.64	0.82
Air Quality ($PM_{2.5}$ > 25 μg/m^3)	1.38	1.20	1.58	1.21	1.08	1.35	1.31	1.18	1.47

Table A4. Association between $PM_{2.5}$ and child morbidity (including diarrhea) adjusting for gender, age, and socioeconomic status.

	Prevalence Analysis			Episode Analysis-Individual			Episode Analysis-Household		
	OR	95% CI		IRR	95% CI		IRR	95% CI	
Female (vs. Male)	0.92	0.83	1.02	0.95	0.89	1.02	1.04	1.02	1.06
Age Group (ref: 0–11 months)									
12–23 months	1.07	0.94	1.21	2.02	1.72	2.38	1.45	1.40	1.49
24–35 months	0.70	0.60	0.80	2.26	1.93	2.66	1.20	1.16	1.24
36–47 months	0.53	0.46	0.62	1.40	1.19	1.65	1.19	1.15	1.24
48–60 months	0.42	0.35	0.50	0.92	0.77	1.09	1.13	1.08	1.19
Wealth Index(ref: Poorest)									
Poor	0.74	0.65	0.84	0.80	0.73	0.87	1.02	1.00	1.04
Least Poor	0.78	0.68	0.90	0.81	0.74	0.89	1.05	1.03	1.08
Air Quality ($PM_{2.5}$ > 25 μg/m^3)	1.19	1.07	1.33	1.16	1.07	1.25	1.10	1.04	1.17

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