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Cooking fuel and risk of under-five mortality in 23 Sub-Saharan African countries: a population-based study

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ABSTRACT
Relationship between cooking fuel and under-five mortality has not been adequately established in Sub-Saharan Africa (SSA). We therefore investigated the association between cooking fuel and risk of under-five mortality in SSA, and further investigated its interaction with smoking. Using the most recent Demographic Health Survey data of 23 SSA countries (n = 783,691), Cox proportional hazard was employed to determine the association between cooking fuel and risk of under-five deaths. The adjusted hazard ratios were 1.21 (95 % CI, 1.10–1.34) and 1.20 (95 % CI, 1.08–1.32) for charcoal and biomass cooking fuel, respectively, compared to clean fuels. There was no positive interaction between biomass cooking fuel and smoking. Use of charcoal and biomass were associated with the risk of under-five mortality in SSA. Disseminating public health information on health risks of cooking fuel and development of relevant public health policies are likely to have a positive impact on a child's survival.

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Indoor air pollution; cooking fuel; under-five mortality; Sub-Saharan Africa

Evidence before this study

Globally, over 4 million deaths occur yearly due to indoor air pollution resulting from cooking fuel. Studies indicate that the under-five children are the most vulnerable group to pollutant cooking fuels with negative health outcome. Moreover, Sub-Saharan Africa (SSA) is the most affected region because 4 out of 5 of its population use solid biomass for cooking, and this may not decrease any time soon in the Sustainable Development Goals (SDGs) era where reduction of deaths as result of hazardous chemicals in the air, water, and soil is a key target. However, most studies have been country-specific and the effects of cooking fuel have majorly focused on ill-health, and not the fatal consequences. This study seeks to fill this gap in a much wider scale in SSA.

Added value of this study

This study explored the fatal effect cooking fuel using a large representative sample of SSA which increases the generalizability of our findings. It also provides evidence that would ensure development

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of appropriate measures to encourage shift to clean and safe cooking fuel, and subsequently achievement of SDG3 targets on the reduction of death resulting from air pollution. Targeting and empowering households would be more effective than focusing on the general population. Policy-makers should therefore integrate pollution control measures with other child health promotion policies, promote behavioural changes, and empower its populace economically.

Introduction

Globally, indoor air pollution (IAP) resulting from cooking fuel was linked to 4.3 million deaths in 2016 in low- and middle-income countries (LMIC). Of those deaths, more than 10 percent are those of children under the age of five (World Health Organization 2014). IAP mainly caused by the use of pollutant cooking fuels such as coal, charcoal, wood, animal dung, and agricultural crops, not only led to premature deaths resulting from acute pneumonia and lower respiratory infections but also higher disability-adjusted life years (DALYs), and hence resulting in an increase in the national and global burden of disease (World Health Organization 2007, World Health Organization 2009). Moreover, among the top 20 most affected counties, 18 were in SSA (International Energy Agency 2016, World Health Organization 2007). SSA is seriously affected because of several underlying factors including the reliance on solid biomass for cooking by the four-fifths of its populace and this poses a greater risk of disease and death of the under-five children (World Health Organization 2007). Indoor cooking using pollutant fuels generate high amount of indoor smoke that contains various substances that have serious health effects. Specifically, exposure to IAP during early childhood impairs the lung function and aggravates the prevailing conditions such as asthma since this is a critical period for the development and maturation of the immune system and various biological systems (Islam et al. 2007; Gauderman et al. 2015); and hence, children's developing organs remains very sensitive to toxic pollutants because they have a higher rate of breathing, absorption, and retention of toxic substances from the air than adults (Davis & Saldiva 1999; Miller et al. 2002; Perlroth & Castelo Branco 2017).

One of the central focus of the Sustainable Development Goal 3 (SDG3) is the target of reducing the number of deaths and illnesses from hazardous chemicals and air including reduction of newborn and under-five deaths (United Nations 2016). However, most studies on IAP as a result of solid fuel in LMIC have majorly focused on ill health such as respiratory illnesses among others (Smith et al. 2000; Gajate-Garrido 2013), which is plausible, and not the fatal effect of the chemical components generated by indoor air pollutants (i.e. sulfur dioxide (SO_2), carbon monoxide (CO), particulates, nitrogen oxides (NO_x), formaldehyde, benzene, arsenic, polyaromatic compounds, and lead) which also remains unclear in the literature (Naeher et al. 2007). Several studies have indicated that children under the age of five compose the most susceptible group for fatalities caused by pollutant cooking fuels (Smith et al. 2000; Gajate-Garrido 2013; Upadhyay et al. 2015). Recent evidence in SSA also indicates that children under five are at a greater risk of death when solid fuel is used in the household (Ezeh et al. 2014; Kleimola et al. 2015). Nevertheless, the relationship between cooking fuel and risk of under-five mortality, on a much wider scale, has not been adequately determined in SSA.

Several factors are also in the interplay of increased or reduced risk of under-five death, for example – while factors such as breastfeeding may act as a protective factor (World Health Organization 2000; Mullany et al. 2008), other pollutants such exposure to tobacco smoke in the household may also contribute to an extra risk of under-five death. Breastfeeding has been found to provide immunologic protection against many infections and respiratory diseases (Goldman 1993; Cushing et al. 1998; Oddy et al. 2003; Field 2005; Tromp et al. 2017). On the other hand, tobacco smoking is another toxic indoor air pollutant that has serious health consequences such as acute and chronic respiratory illnesses that would lead to mortality of the under-five children (Charoenca et al. 2013; Sigaud et al. 2016). However, little is known on the interaction between exposure to smoke from cooking fuel and tobacco smoke. In this study, we therefore hypothesized that exposure smoke from both cooking fuel and tobacco in the household increases the risk of under-five mortality in an additive scale.

In the present study, we explored the association between type cooking fuel and risk of under-five mortality in SSA, further investigating the interaction between exposure to smoke from cooking fuel and tobacco smoke on the under-five mortality.

Methods

Study population and data sources

We used the most recent cross-sectional data of 23 countries in SSA (*n* = 783,691), collected within 2010 to 2014 through the Demographic Health Survey (DHS). The countries included in the study were Benin, Bukina Faso, Burundi, Comoros, Congo, Côte d'Ivoire, DRC, Ethiopia, Gabon, Gambia, Guinea, Kenya, Liberia, Mali, Mozambique, Nigeria, Namibia, Rwanda, Sierra Leone, Togo, Uganda, Zambia, and Zimbabwe. A stratified sampling technique based on a two-stage cluster sampling design was employed to sample the households before collecting information for women (aged 15–49 years) and their children. The total number of children for each country is presented in Table 1. The DHS program obtained ethical approval from the ethics committees of each country before conducting the survey in collaboration with the ministries of health. Detailed information of the survey is available at http://dhsprogram.com. Briefly, the DHS is a cross-sectional nationally representative household survey that collects health information through a face-to-face interview. In sampling the households, a stratified two-stage cluster sampling approach is used where the first stage involves sampling of enumeration areas from national census files by considering the residence and regional levels. In the second stage, however, households are sampled in the selected enumeration area. The trained field staffs conduct the interviews under the supervision of coordinators who are responsible for data collection quality. The participants signed an informed consent before data collection, and all the data were anonymized. The ethical standards of DHS program are described elsewhere (Adetunji and Shelton 2011), while the data and the final report of each country, sampling, and response rate is found on the DHS Program's website (Demographic Health Survey Program 2016).

Measurements

Under-five mortality

To define our outcome indicator, all-cause mortality of the under-five with time-to-event being age in months (0 – 59) was used (1 for yes; 0 otherwise). All-cause mortality was used because of the data limitation resulting from the uncollected information on causes of death. The under-five mortality question asked whether the child was alive or dead at the time of the interview; and if the child was dead, age at death was asked.

Cooking fuel exposure assessment

Our exposure variable was type of cooking fuel used in the household. It had 11 categories, and for the purpose of our analysis we classified it into four main groups which include: 'clean' fuel (electricity, natural gas, biogas or liquefied petroleum gas) as the reference group; biomass cooking fuels divided as 'charcoal' (i.e. majorly used indoors) and other 'biomass' fuels – mainly used outdoors for cooking (wood, straw/shrubs/grass, agricultural crops, or animal dung); and 'other' pollutant cooking fuel (coal, lignite or paraffin/kerosene).

Covariate information

Several variables were considered in this study. These included the proxy measure of the level of exposure to household air pollution, the location of household kitchen categorized in three groups (located in the house, outdoors, or in a separate building), the country, the place of residence (urban or rural), and the administrative provinces of each country. Moreover, we included children's characteristics: the binary variables of sex and breastfeeding status, and the discrete variable, the number of under-five

Table 1. Characteristics of children five and under in Sub-Saharan Africa, by cooking fuel (n = 783,691).

	Cooking fuel type				
	Clean *n* ($\%_{wt}$)[a]	Charcoal *n* ($\%_{wt}$)[a]	Biomass *n* ($\%_{wt}$)[a]	Other *n* ($\%_{wt}$)[a]	*p*-value
Total number	32,037 (4.7)	111,885 (14.6)	612,569 (76.7)	27,200 (4.0)	
Kitchen location					
Separate building	3,280 (1.0)	30,494 (9.0)	264,987 (88.0)	6,104 (2.0)	< 0.001
In the house	26,405 (14.3)	26,399 (12.8)	141,105 (66.4)	11,373 (6.6)	
Outdoors	2,352 (1.0)	54,992 (22.1)	206,477 (72.7)	9,723 (4.2)	
Country, year					
Bukina Faso, 2010	656 (1.6)	1,369 (2.5)	51,257 (96.0)	8 (0.0)	< 0.001
Benin, 2011/12	874 (2.8)	6,879 (19.6)	34,599 (76.6)	361 (1.0)	
Burundi, 2010	17 (0.0)	2,790 (6.7)	20,377 (93.3)	0 (0.0)	
DRC, 2013/2014	619 (1.3)	11,555 (24.7)	44,107 (73.9)	84 (0.2)	
Congo, 2011/12	1,550 (12.7)	5,394 (33.9)	20,451 (46.5)	927 (6.9)	
Côte d'Ivoire, 2011/12	1,672 (10.8)	3,404 (14.3)	20,153 (74.8)	52 (0.2)	
Ethiopia, 2011	337 (0.5)	2,940 (3.9)	38,810 (94.9)	750 (0.6)	
Gabon, 2012	11,550 (84.4)	496 (1.4)	5,731 (13.6)	77 (0.6)	
Gambia, 2013	65 (0.3)	3,601 (17.9)	20,153 (81.7)	18 (0.0)	
Guinea, 2012	34 (0.1)	5,243 (22.4)	20,554 (77.4)	16 (0.1)	
Kenya, 2014	1,113 (5.5)	5,726 (16.0)	29,282 (72.9)	823 (5.7)	
Comoros, 2012	235 (2.4)	170 (1.3)	8,016 (84.0)	1,425 (12.3)	
Liberia, 2013	9 (0.1)	3,694 (27.6)	20,712 (72.4)	1 (0.0)	
Mali, 2012/13	83 (0.3)	3,186 (10.1)	24,684 (89.4)	110 (0.3)	
Mozambique, 2011	1,185 (2.1)	5,369 (12.8)	27,586 (84.1)	477 (1.0)	
Nigeria, 2013	1,509 (1.3)	2,952 (2.8)	94,299 (81.1)	15,294 (14.9)	
Namibia, 2013	3,654 (43.4)	49 (0.4)	5,463 (54.2)	93 (2.1)	
Rwanda, 2010	3 (0.0)	2,603 (7.2)	27,988 (92.8)	1 (0.0)	
Sierra Leone, 2013	15 (0.0)	5,967 (13.5)	37,347 (86.5)	28 (0.0)	
Togo, 2013/14	584 (2.9)	17,793 (64.5)	324 (1.4)	6,380 (31.2)	
Uganda, 2011	109 (0.3)	5,578 (17.2)	22,001 (82.4)	39 (0.1)	
Zambia, 2013/14	2,390 (6.9)	15,103 (33.8)	25,489 (59.3)	30 (0.0)	
Zimbabwe, 2010/11	3,774 (21.7)	24 (0.1)	13,186 (76.6)	206 (1.6)	
Residence					
Urban	27,008 (15.0)	73,315 (34.2)	100,245 (39.3)	21,457 (11.6)	< 0.001
Rural	5,029 (0.6)	38,570 (6.6)	512,324 (91.9)	5,743 (0.9)	
Sex					
Male	16,200 (4.7)	56,615 (14.5)	312,434 (76.8)	13,771 (4.0)	0.042
Female	15,837 (4.8)	55,270 (14.7)	300,135 (76.4)	13,429 (4.1)	
Breastfeeding status					
No	26,081 (6.2)	75,853 (15.8)	372,675 (73.3)	20,064 (4.7)	< 0.001
Yes	5,956 (2.4)	36,032 (12.6)	239,894 (82.2)	7,136 (2.8)	
No. of under-5 in HH, mean (SD)[b]	1.2 (1.1)	1.5 (1.2)	1.7 (1.4)	1.2 (1.1)	< 0.001
Mother's age, mean (SD)[b]	35.7 (7.7)	34.9 (7.7)	35.6 (7.9)	35.2 (7.6)	< 0.001
Family size, mean (SD)[b]	6.1 (3.1)	7.0 (3.7)	7.5 (4.1)	5.7 (3.0)	< 0.001
Member smoking in HH					
No	26,132 (5.0)	89,603 (15.2)	466,620 (75.1)	24,087 (4.6)	< 0.001
Yes	5,905 (3.8)	22,282 (12.4)	145,949 (81.8)	3,113 (2.0)	
Wealth index					
Poorest	2,158 (0.6)	10,970 (4.4)	189,324 (94.9)	322 (0.1)	< 0.001
Poorer	3,686 (1.7)	11,935 (6.6)	156,423 (91.4)	568 (0.3)	
Middle	2,929 (2.4)	15,509 (10.0)	136,339 (86.0)	2,328 (1.6)	
Richer	5,798 (5.1)	27,779 (21.2)	97,537 (66.5)	8,826 (7.2)	
Richest	17,466 (18.2)	45,692 (39.7)	32,946 (27.4)	15,156 (14.7)	
Mother's education					
No education	2,065 (0.7)	37,872 (9.2)	355,694 (88.9)	4,387 (1.2)	< 0.001
Primary	8,219 (3.5)	39,221 (16.2)	188,936 (76.4)	7,876 (3.9)	
Secondary	17,426 (16.3)	31,018 (27.4)	63,700 (45.0)	12,023 (11.3)	
Higher	4,327 (33.5)	3,774 (24.3)	4,239 (23.6)	2,914 (18.6)	
Mother's occupation					
Not employed	10,645 (5.8)	28,033 (15.2)	154,171 (76.1)	5,010 (2.9)	< 0.001
Professional/office-related	5,600 (28.5)	5,943 (24.6)	9,218 (35.6)	2,653 (11.3)	
Sales	8,435 (6.0)	38,086 (23.3)	106,217 (61.6)	13,039 (9.0)	
Farming	1,480 (0.3)	21,069 (6.4)	281,392 (92.9)	1,077 (0.3)	
Other services	5,877 (8.3)	18,754 (20.9)	61,571 (63.6)	5,421 (7.2)	

(*Continued*)

Table 1. *(Continued).*

	Cooking fuel type				
	Clean *n* ($\%_{wt}$)[a]	Charcoal *n* ($\%_{wt}$)[a]	Biomass *n* ($\%_{wt}$)[a]	Other *n* ($\%_{wt}$)[a]	*p*-value
Father's occupation					
Not employed	702 (1.1)	10,389 (13.9)	55,254 (83.9)	718 (1.1)	< 0.001
Professional/office-related	10,194 (16.0)	16,714 (23.8)	43,361 (52.2)	5,352 (8.1)	
Sales	3,202 (5.7)	13,999 (22.0)	44,641 (64.6)	4,661 (7.7)	
Farming	1,709 (0.3)	28,751 (6.7)	352,940 (92.5)	2,341 (0.5)	
Other services	16,230 (10.1)	42,032 (24.2)	116,373 (56.7)	14,128 (9.0)	
Under-5 mortality					
Alive	30,215 (5.1)	100,502 (15.1)	529,813 (75.6)	25,000 (4.2)	< 0.001
Dead	1,822 (2.1)	11,383 (11.6)	82,756 (83.8)	2,200 (2.5)	

[a]*n* is unweighted number, while the row percentages ($\%_{wt}$) were weighted using a Taylor series linearization by incorporating the primary sampling unit, sampling strata (cluster), country, and sampling weights.
[b]Linear regression was used for continuous variables; HH, household.

children in the household. We also included family characteristics, including mother's age and the family size, as continuous variables. We also included a potential household pollutant: household tobacco smoke (a binary variable). Furthermore, our analyses included indicators of socioeconomic status (SES), such as household wealth index (poorest, poor, middle, rich, and richest), mother's education (no education, primary, and secondary and higher), mother's and father's occupation (unemployed, professional/office-related, sales, farming, and other services), which were all previously identified as potential confounders (Wichmann & Voyi 2006; Rinne et al. 2007; Rehfuess et al. 2009; Kashima et al. 2010; Ezeh et al. 2014; Naz et al. 2015, 2016).

Statistical analysis

The association between exposure to smoke from cooking fuel and the risk of under-five mortality in SSA was investigated using a four-stage of analyses. First, the distribution of children exposed to smoke from solid cooking fuels was mapped for each SSA country by place of residence. The mapping of these proportions was executed using Google Earth Pro and Epi Info 7.2 (Google Earth Pro 2015; Dean et al. 2016). Secondly, the characteristics of the children by cooking fuel category were compared through a χ^2 test for categorical variables and linear regression for continuous independent variables. Thirdly, Cox proportional hazards models were used to analyze the association between exposure to smoke from cooking fuel and the risk of under-five mortality with the time-to-event variable being the age in months. Cox proportional hazard model is a survival model that consider the time to the occurrence of an event, in this case – age in months before a child's death. Two models were fitted in this study. In the first model, we evaluated whether the risk of under-five mortality varied across the indicators by fitting simple Cox proportional hazard models. We then fitted the second model as below:

$$\lambda_i(t) = \lambda_0(t)\exp(\beta_1 X_{i1} + \beta_2 X_{i2} + \ldots + \beta_n X_{in})$$

where λ is the hazard function and i is the child at time t; β is the regression coefficient; X is the variable; and n is the number of variables. The λ_0 is the baseline hazard function when $\exp(X\beta) = 1$.

To adjust for the sampling design, all analyses were weighted using complex survey analysis – which employs Taylor series linearization – by incorporating the sampling weights, pooled countries, sampling strata (cluster), and primary sampling unit. The hazard ratio (HR) and 95 % confidence interval (CI) of each indicator was presented for all variables.

Finally, we estimated the interaction – in an additive scale – between smoke from cooking fuel and tobacco smoke on the under-five deaths. We used two indices to approximate the risk ratio from the adjusted HRs, and these were the relative excess risk due to interaction (RERI) and the attributable proportion due to interaction (AP). RERI indicates part of the total effect that is due to interaction (RERI $\approx HR_{11} - HR_{10} - HR_{01} + 1$) (VanderWeele 2011); an RERI less than 0 implies a negative interaction or less than additivity (i.e. combining exposure to smoke from cooking fuel and tobacco smoke can have extra risk effects). AP indicates the proportion of the combined effect that is due to interaction ($AP = RERI/HR_{11}$); an AP less than zero implies a negative interaction. We employed the 'ici' command in Stata to estimate the interaction effect and associated 95 % confidence interval (CI) using the matrix of the hazard regression model (Model 2). Some authors have encouraged the use of bootstraps in estimating the 95 % CI (DiCiccio & Efron 1996), while others found that the 95 % CI results tend to be similar in large studies when using different approaches (Richardson & Kaufman 2009). Since our study included a large sample size, we therefore used the variance and covariance of the coefficients to estimate the 95 % CI (Hosmer & Lemeshow 1992; Zou 2008). All analyses were carried out in Stata 13.1 (StataCorp 2013).

Results

Sample characteristics

In Table 1, the socioeconomic and demographic factors of the children in each cooking fuel group are presented. The majority of children in SSA were exposed to smoke from biomass cooking fuel (76.7 %), living in rural areas, from poor families, and had parents without formal educations who were engaged in farming activities; 91.9 % of the under-five children living in rural areas were exposed to smoke from biomass cooking fuels, while for poorest families 94.9 % were exposed to biomass cooking fuels. Moreover, 88.9 % and 92.9 % of children of the uneducated mothers and were involved in farming activities were exposed to smoke from biomass cooking fuel, respectively. All the indicators were statistically significant at $p < 0.001$, except for the child's sex ($p = 0.042$).

Geographical profile of solid cooking fuel by residence

The distributions of solid cooking fuel by place of residence (categorized as urban and rural) for each country are shown in Figure 1. The proportion of children under five exposed to smoke from biomass cooking fuel, in both urban and rural areas, of some countries (Bukina Faso, Ethiopia, Gambia, Mali Sierra Leone, and Rwanda) were the highest. Moreover, the highest proportions were seen in rural residences. Even though exposure to smoke from the use of solid biomass for cooking appeared low in Togo, over 91 % and 98 % of urban and rural children, respectively, children exposed to smoke from use of biomass and charcoal/coal, combined was still high. Overall, the majority of the children were exposed to smoke from solid cooking fuel (charcoal and biomass combined) with Gabon (15.1 %) being the lowest and some countries (i.e. Bukina Faso, Burundi, DRC, Ethiopia, Gambia, Gabon, Liberia, Mali, Rwanda, Sierra Leone, and Uganda) as high as 98 %.

Cooking fuel and risk of under-five mortality in SSA

Table 2 presents the crude and adjusted HRs of the association between exposure to smoke from cooking fuel and risk of under-five mortality. Use of different types of cooking fuel was significantly associated with the risk of under-five mortality in SSA before and after controlling for other indicators. Before adjustment, children who were exposed to emission from charcoal (HR = 1.97; 95 % CI, 1.80–2.16), biomass (HR = 2.67; 95 % CI, 2.46–2.90), and other fuels (HR = 1.49; 95 % CI, 1.34–1.66) were at a higher risk of mortality than those who were exposed to clean cooking fuel. But after adjusting for all the variables in Model 2, the HRs for those exposed to charcoal and biomass fuels fell to 1.21 (95 % CI, 1.10–1.34) and 1.20 (95 % CI, 1.08–1.32), respectively, but were still statistically significant at $p < 0.001$; while the risk of death for children exposed to other fuels attenuated.

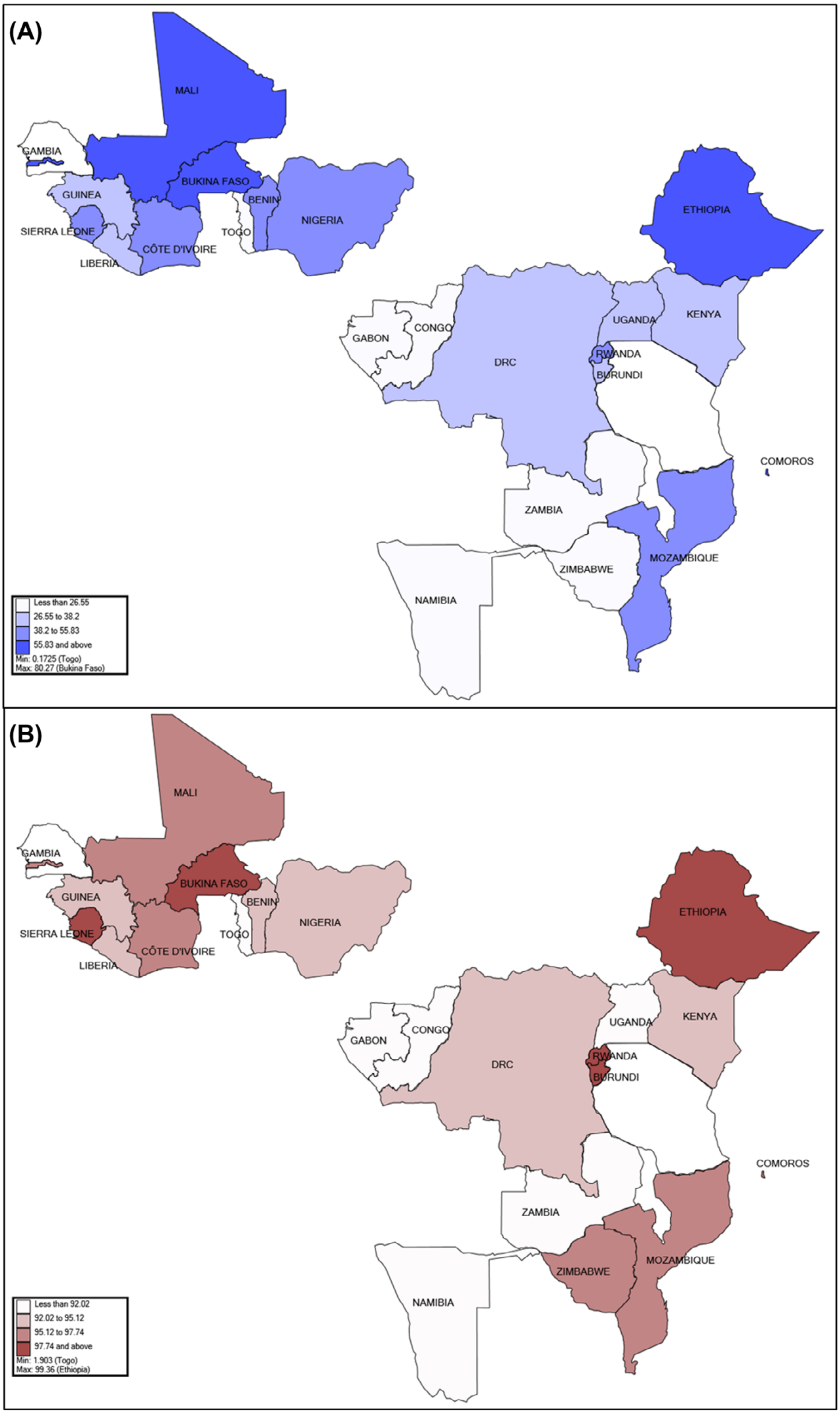

Figure 1. (Color online) The geographical distribution of solid cooking fuel usage by place of residence, (A) urban and (B) rural.

Table 2. Cox proportional hazard ratios (HRs) for the risk of under-five mortality resulting from cooking fuel (n = 783,691).

	Model 1	Model 2
	Crude HR (95 % CI)	Adjusted HR (95 % CI)[a]
Cooking fuel (Ref: Clean)		
Charcoal	1.97 (1.80, 2.16)***	1.21 (1.10, 1.34)***
Biomass	2.67 (2.46, 2.90)***	1.20 (1.08, 1.32)***
Other	1.49 (1.34, 1.66)***	1.01 (0.90, 1.14)
Kitchen location (Ref: Separate building)		
In the house	1.10 (1.06, 1.14)***	1.06 (1.03, 1.10)***
Outdoors	1.08 (1.05, 1.11)***	0.98 (0.95, 1.01)
Country (Ref: Benin)		
Bukina Faso, 2010	1.92 (1.79, 2.05)***	1.96 (1.83, 2.09)***
Burundi, 2010	1.85 (1.71, 2.00)***	1.92 (1.77, 2.08)***
DRC, 2013/14	1.65 (1.52, 1.80)***	1.78 (1.64, 1.93)***
Congo, 2011/12	1.08 (0.98, 1.18)	1.25 (1.13, 1.37)***
Côte d'Ivoire, 2011/12	1.33 (1.21, 1.46)***	1.45 (1.33, 1.58)***
Ethiopia, 2011	1.48 (1.37, 1.61)***	1.48 (1.37, 1.61)***
Gabon, 2012	0.64 (0.57, 0.73)***	0.95 (0.83, 1.09)
Gambia, 2013	0.82 (0.73, 0.92)***	0.94 (0.83, 1.06)
Guinea, 2012	1.69 (1.56, 1.84)***	1.68 (1.55, 1.82)***
Kenya, 2014	0.84 (0.76, 0.91)***	0.94 (0.86, 1.03)
Comoros, 2012	0.52 (0.42, 0.63)***	0.62 (0.51, 0.75)***
Liberia, 2013	1.87 (1.72, 2.03)***	2.15 (1.98, 2.34)
Mali, 2012/13	1.36 (1.24, 1.49)***	1.31 (1.14, 1.51)***
Mozambique, 2011	1.74 (1.61, 1.89)***	1.81 (1.67, 1.96)***
Nigeria, 2013	1.83 (1.70, 1.97)***	1.97 (1.84, 2.12)***
Namibia, 2013	0.69 (0.60, 0.79)***	0.93 (0.81, 1.06)
Rwanda, 2010	1.67 (1.55, 1.80)***	1.97 (1.82, 2.12)***
Sierra Leone, 2013	2.59 (2.40, 2.79)***	2.73 (2.54, 2.95)***
Togo, 2013/14	1.19 (1.08, 1.29)***	1.38 (1.26, 1.52)***
Uganda, 2011	1.58 (1.45, 1.72)***	1.73 (1.51, 1.97)***
Zambia, 2013/14	1.37 (1.27, 1.48)***	1.57 (1.45, 1.70)***
Zimbabwe, 2010/11	0.78 (0.71, 0.87)***	0.91 (0.82, 1.02)
Residence (Ref: Urban)	1.54 (1.49, 1.60)***	1.08 (1.04, 1.12)***
Child's sex (Ref: Male)	0.94 (0.92, 0.95)***	0.94 (0.93, 0.96)***
Breastfeeding status (Ref: No)	1.49 (1.46, 1.52)***	1.03 (1.01, 1.06)**
No. of under-5 in HH (in 1 unit increment)	1.08 (1.07, 1.09)***	1.05 (1.03, 1.06)***
Mother's age (in 1 year increment)	0.95 (0.95, 0.95)***	0.95 (0.95, 0.96)***
Family size (in 1 unit increment)	0.98 (0.98, 0.99)***	0.97 (0.97, 0.98)***
Member smoking in HH (Ref: No)	1.18 (1.15, 1.22)***	1.09 (1.06, 1.12)***
Wealth index (Ref: poorest)		
Poorer	0.92 (0.89, 0.95)***	0.95 (0.92, 0.98)***
Middle	0.79 (0.76, 0.82)***	0.87 (0.84, 0.90)***
Richer	0.68 (0.66, 0.71)***	0.80 (0.77, 0.83)***
Richest	0.47 (0.45, 0.50)***	0.65 (0.61, 0.69)***
Mother's education (Ref: No education)		
Primary	0.82 (0.80, 0.84)***	0.91 (0.89, 0.94)***
Secondary	0.61 (0.58, 0.63)***	0.83 (0.79, 0.87)***
Higher	0.36 (0.32, 0.41)***	0.68 (0.59, 0.79)***
Mother's occupation (Ref: Not employed)		
Professional/office-related	0.45 (0.41, 0.50)***	0.88 (0.79, 0.98)*
Sales	0.95 (0.91, 0.98)**	1.02 (0.98, 1.06)
Farming	1.13 (1.10, 1.17)***	1.04 (1.00, 1.07)*
Other services	0.97 (0.93, 1.02)	1.01 (0.97, 1.05)
Father's occupation (Ref: Not employed)		
Professional/office-related	0.76 (0.72, 0.81)***	0.95 (0.85, 1.07)
Sales	1.13 (1.06, 1.20)***	1.02 (0.92, 1.14)
Farming	1.21 (1.16, 1.27)***	0.98 (0.88, 1.09)
Other services	0.95 (0.91, 1.01)	1.00 (0.90, 1.12)

[a]Adjusted for kitchen location, country, residence and administrative provinces (provinces not shown), child's sex, breastfeeding status, number of under-5 children, mother's age and family size, wealth index, mother's education, mother's occupation, and father's occupation.

*$p \le 0.05$; **$p \le 0.01$; ***$p \le 0.001$.

Table 3. Hazard ratios (HRs) of risk of under-five mortality by cooking fuel and smoking in the household in Sub-Saharan Africa (n = 783,691).

Cooking fuel by smoking status	No. of dead children	No. of children	HR (95 % CI) [a]	$RERI_{HR}$ (95 % CI)	Attributable proportion due to interaction
Clean fuel					
No smoking	1453	26,132	1.00		
Smoking	369	5905	1.05 (0.86, 1.27)		
Charcoal					
No smoking	8692	89,603	1.18 (1.05, 1.32)**		
Smoking	2691	22,282	1.40 (1.24, 1.58)***	0.17 (– 0.05, 0.38)	0.12 (– 0.04, 0.27)
Biomass					
No smoking	61,689	466,620	1.19 (1.07, 1.33)**		
Smoking	21,067	145,949	1.29 (1.15, 1.44)***	0.05 (– 0.16, 0.25)	0.04 (– 0.12, 0.19)
Other					
No smoking	1932	24,087	1.00 (0.88, 1.13)		
Smoking	268	3113	1.17 (0.92, 1.49)	0.12 (– 0.21, 0.45)	0.10 (– 0.16, 0.37)

[a]Adjusted for kitchen location, country, residence and administrative provinces, child's sex, number of under-5 children, mother's age and family size, wealth index, mother's education, mother's occupation, and father's occupation; RERI, relative excess risk due to interaction.
**$p \le 0.01$; ***$p \le 0.001$.

Other factors associated with risk of under-five mortality

In general, all the variables were statistically associated with the risk of under-five mortality before adjustment in Model 1 (Table 2). But, after adjustment, only those who had kitchens in their house were more at risk for under-five mortality than those who had kitchens located in separate buildings (HR = 1.06; 95 % CI, 1.03–1.10). The majority of the countries were at a higher risk of under-five mortality than Benin, with Sierra Leone having the highest HR of 2.73 (95 % CI, 2.54–2.95) while Comoros was the lowest at 38 % less risk of under-five mortality than Benin. Children living in rural areas (HR = 1.08; 95 % CI, 1.04–1.12), still breastfeeding (HR = 1.03; 95 % CI, 1.01–1.06) were at more risk of death than those in urban areas and had stopped breastfeeding, respectively. Female children were at 6 % less risk of death than the male children. An increase in the mother's age by one year lowered the risk of death by 5 %. A child who was exposed to tobacco smoke in the household was at 9 % higher risk of death than those who were not exposed. The richest households (HR = 0.65; 95 % CI, 0.61–0.69) and mothers who had higher education levels (HR = 0.68; 95 % CI, 0.59–0.79) and professional jobs (HR = 0.88; 95 % CI, 0.79–0.98) were at less risk of under-five death than the poorest households, uneducated, and unemployed mothers, respectively. Still, all the SES indicators were statistically significant after adjustment, except for father's occupation.

Interaction between cooking fuel and breastfeeding

The risk of under-five death in households that were using charcoal as cooking fuel and were exposed to tobacco smoke was 40 %, while that of children exposed to smoke from biomass cooking fuel and tobacco smoke was 29 %. The adjusted HRs of children exposed to smoke from both charcoal cooking fuel and tobacco (HR = 1.40; 95 % CI, 1.24–1.58) and smoke from both biomass cooking fuel and tobacco (HR = 1.29; 95 % CI, 1.15–1.44) were higher as compared to the adjusted HRs of children exposed to smoke from charcoal and biomass cooking fuels in Table 2, respectively. There was a sign of positive interaction between exposure to smoke from cooking fuel and tobacco smoke on the under-five deaths, but the RERI and AP in all the cooking fuel types were not statistically significant (Table 3).

Discussion

Reduction of the number of deaths from hazardous chemicals and air by 2030 is entrenched in SDG3 targets, and yet, the primary household air pollutant in SSA still remain solid cooking fuels, owing to an inadequate access of modern energy. The result of this has been nearly 600,000 premature deaths, 2016 estimate (World Health Organization 2007; International Energy Agency 2016). Recently, a growing awareness of the health-related outcomes associated with IAP has brought attention to the under-five mortality in LMIC, of which SSA and Southeast Asia account for the highest household air pollution-related deaths (World Health Organization 2014). An understanding of the relationship between the use of cooking fuel and risk of under-five death is therefore essential. Consequently, we explored the association between exposure to smoke from household cooking fuel and risk of under-five mortality in SSA, and further tested the interaction effect between exposure to smoke from cooking fuel and tobacco smoke on the under-five mortality.

Consistent with previous studies (Ezeh et al. 2014; Naz et al. 2016), we found that use of cooking fuel was significantly associated with the risk of under-five mortality in SSA. The risk of death was also higher in the proxy indicator of the level of exposure, kitchen location, with a greater risk realized in households with indoor kitchens. This result indicates that younger children who stay indoors and/or are carried by mothers during cooking were at a greater risk of death (de Francisco et al. 1993; Bruce et al. 2000; Smith & Mehta 2003; Munroe & Gauvain 2012). Kitchen location has previously been found to be an important risk factor of under-five mortality in Africa (Rehfuess et al. 2009). Our results indicate that the risk of under-five death can be reduced with a kitchen distinct from the main house, even with use of pollutant cooking fuels as the main source of household energy.

Smoke from charcoal and biomass cooking fuels contain major indoor pollutants, such as carbon monoxide (CO) and very small particulates ($PM_{2.5}$), among other hazardous chemicals, and these chemicals increases the risk of under-five mortality. Hence, our findings on charcoal and biomass use have biologically plausible implications on the risk of death for the children exposed to the smoke from these cooking fuels. Even though there was no interaction between exposure to smoke from cooking fuel and tobacco smoke on under-five deaths, exposure to smoke from charcoal and biomass fuels together with tobacco smoke had an extra increase in the risk of under-five death with the HRs for charcoal-tobacco smoke (HR = 1.40; 95 % CI, 1.24–1.58) and biomass-tobacco smoke (HR = 1.29; 95 % CI, 1.15–1.44) being statistically significant, unlike another study that did not find the effect of secondhand smoking (Mishra et al. 2005).

Our study found significant differences between and within the countries, with the children in rural areas being at a greater risk of death than those in urban areas, and this too was consistent with previous studies indicating that rural residence is a strong risk factor of under-five mortality (Bassani et al. 2010; Ezeh et al. 2014; Naz et al. 2016). The regional differences may be as a result of regional factors such as climatic conditions that may pose risk of respiratory diseases in infants and children. Clearly, the proportions of children exposed to smoke from biomass cooking fuels in SSA were high in rural areas (91.9 %). Inadequate access to clean cooking fuels, generally considered as safe, can explain these high figures. A greater proportion of children in some countries were highly exposed to biomass fuel in urban areas (i.e. Bukina Faso, Comoros, Ethiopia, Gambia, and Mali) and rural residence (i.e. Bukina Faso, Burundi, Ethiopia, Rwanda, and Sierra Leone) (Figure 1). Four out of five people in the SSA population relied entirely on biomass fuel from wood, straw/shrubs/grass, agricultural crops, and animal dung for domestic cooking energy (International Energy Agency 2016). Incomplete combustion of biomass burning emits many toxic substances such as small particles, CO, NO_2, formaldehyde, acrolein, benzene, toluene, polyaromatic hydrocarbons among others. This study also found that male children were at a higher risk of death than females, consistent with other studies (Bassani et al. 2010; Ezeh et al. 2014). The finding that male children were at a higher risk of death than the female children; may be due to the longevity and survival of a female child who has a natural biological advantage over male child (Gurusamy 2007). In addition, other factors that were significantly associated with the risk of under-five mortality included the number of under-five children in the household, mother's age, and the number of household members.

Even though breastfeeding has been shown to protect infants against infection and reduce the risk of respiratory illness (Cushing et al. 1998; Oddy et al. 2003; Tromp et al. 2017), we found that children who were still breastfeeding were at a greater risk of death than those who had stopped. The reason for this kind of relationship could have been that younger children who were still breastfeeding may have been exposed to higher concentrations of smoke since their mothers may still carry them while cooking. In SSA, where the usage of biomass for cooking fuel remains high, mothers should be encouraged to continue breastfeeding beyond the minimum period usually advocated (6 months) at the same time reduce child's exposure to smoke from pollutant cooking fuels. Although research on breastfeeding beyond two years is rare, continued breastfeeding seems to remain an important source of nutrition and protection against disease (Onyango et al. 2002; Perrin et al. 2013). Breastfeeding has been found to be effective only in the first 11 months of the life of a child in lowering the risk of death among children in a study of household air pollution from cooking fuel (Ezeh et al. 2014).

Our study also found SES (e.g. wealth index, mother's education, and mother's occupation) to be a significant factor associated with the risk of under-five mortality. Children from richer households and who had educated mothers with professional jobs were at a lower risk of mortality than their counterparts. Poorer households are more inclined to using solid pollutant fuels, thus explaining the relationship (Larrea & Kawachi 2005). In light of these findings, reduction of serious health problems associated with cooking fuel in SSA requires substitution of charcoal, wood, animal dung or agricultural crops to more efficient, modern, and less polluting cooking fuels. Nevertheless, since poorer households may have non-immediate changeable socioeconomic conditions, several other aspects such as behavioural changes may be necessary to reduce exposure to toxic indoor air pollutants. Low-cost or no-cost behavioural changes such as keeping children away from exposure to toxic substances, using dry wood for cooking, reducing cooking time by use of lids or improved cooking pans, opening doors and windows to improve ventilation can only be achieved if public health promotion is increased. Moreover, control of other indoor air pollutants may be necessary to improve indoor air quality and these include no tobacco smoking at home, non-use of pesticides and such like when a child is indoors, and cleaning molds and mites (World Health Organization & United Nations Environment Programme 2010).

One major barrier to improving under-five health outcomes in SSA is lack of awareness of the toxic effect of indoor air pollutants such as cooking fuel. Hence, policy-makers should consider reviewing the community and national health promotion strategy to reach and constantly educate the populace on preventive measures to exposure to toxic indoor pollutants through mass media and local community meetings. The use of mass media to transmit reliable information can inspire debates around these subjects and offer a platform for behavioural changes. Another setback to achieving desirable health outcome is limited income which leads to lack of access to clean fuel, especially in poor geographical locations that depend more on biomass cooking fuels. Community economic empowerment is therefore necessary to realize a rapid change in the non-use of solid cooking fuels, and subsequently, an improved health. Another major barrier is systemic-related, which inhibit parents of sick children to have immediate access to quality health care services. A lot more needs to be done to improve access to health care services and to encourage parents to seek immediate health care attention in case the child is unwell so as to reduce preventable under-five deaths. The health ministry should improve, equip, and staff available health facilities, and to build new ones in marginalized regions, so as to enhance access to quality health services. An independent evaluation team that would oversee progress in the under-five health may also be necessary, especially in the most affected regions.

Strengths and limitations

One of the strengths of our study is the national and regional representativeness using several countries in SSA to estimate the risk of under-five deaths from exposure to smoke from cooking fuel, and this increases generalizability of our finding. However, there were several limitations related to the exposure and outcome indicators. This study was based on cross-sectional data collected retrospectively, and hence a true measure of causality could not be ascertained as a result of potential biases such as recall, misclassification, and selection as well as extrapolation of characteristics at time of interview to the deceased child. Future studies should therefore consider developing a prospective study that would enable adequate assessment of the effects of micro-environmental risk factors and health outcomes. Secondly, we used all-cause mortality because detailed information on the child's health and causes of death was lacking. Children in SSA die from several other factors unrelated to IAP such as infectious diseases with malaria being the main cause of death. Studies that would follow-up children in SSA to determine the true causal relationship between IAP and under-five mortality are therefore necessary. The third limitation included inability to adjust for the unmeasured potential confounders, such as other details of tobacco smoking (e.g. number of cigarette smoked in the household), infectious diseases of both the living and dead children; some children might as well have died as a result of several other environmental-, social-, genetic-, and health-related factors. Fourthly, the effect of smoke from cooking fuel might have been underestimated because as children grow older they tend to be more active and participate in outdoor activities, leading to increased exposure to polluted ambient environment. Moreover, ventilation information and other information such as cooking frequency and the level of exposure to polluted air. The DHS survey data were collected for general purposes and hence might be limited in the information contained therein, including the historical use of cooking fuel, which can change with changes in household income (Reddy et al. 1997). A previous study found that even though households may use one primary fuel, they would frequently switch to another (Balakrishnan et al. 2011). Finally, some households might have used a combined source of cooking fuel (i.e. clean and pollutants), but this information was not available in the data.

Conclusions

The use of solid cooking fuel increased the risk of under-five death in SSA. However, the use of cooking fuel and death of the under-five children vary between and within countries implying lack of a single generalized result. Spreading public health information on the health risks of using pollutant cooking fuels, economic development, improving house designs, and developing public health policies is likely to make a positive impact on a child's survival in SSA.

Disclosure statement

The authors report no conflicts of interest.

Data availability statement

The data-sets supporting the conclusions of this article are available upon request in the Demographic and Health Surveys program repository, [unique persistent identifier and hyperlink to data-sets in http://dhsprogram.com].

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