Predictors of indoor particulate matter and carbon monoxide concentrations in households of an informal urban settlement in Fort Portal city, Uganda

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Abstract

Background

Poor indoor air quality (IAQ) is a leading cause of respiratory and cardiopulmonary illnesses. Particulate matter ($PM_{2.5}$) and carbon monoxide (CO) are critical indicators of IAQ, yet there is limited evidence of their concentrations in urban informal settlements in low-income countries.

Objective

This study assessed household characteristics that predict the concentrations of $PM_{2.5}$ and CO within households in an informal settlement in Fort Portal City, Uganda.

Methodology:

A cross-sectional study was conducted in 374 households. Concentrations of $PM_{2.5}$ and CO were measured using Multi-purpose Laser Particle detector and the Carbon Monoxide IAQ Meter respectively. Data on household characteristics were collected using a structured questionnaire and an observational checklist. Data were analysed using STATA version 14.0. Linear regression was used to establish the relationship between $PM_{2.5,}$ CO concentrations and household characteristics.

Results

The majority, 88.8% (332/374) of the households used charcoal for cooking. More than half, 51.9% (194/374) cooked from outdoors. Cooking areas had significantly higher $PM_{2.5}$ and CO concentrations compared to the living area ($t = 18.14$, $p \leq 0.05$) and ($t = 5.77$ $p \leq 0.05$) respectively. Cooking from outdoors was associated with a 0.112 increase in the $PM_{2.5}$ concentrations in the cooking area (0.112 [95% CI: -0.069, 1.614; p = 0.033]). Cooking with moderately polluting fuel was associated with a 0.718 increase in CO concentrations (0.718 [95% CI: 0.084, 1.352; p = 0.027]) in the living area.

Discussion

The concentration of $PM_{2.5}$ and CO during the cooking time for both the cooking area and the living area were above the World Health Organisation Air Quality Guideline of 25μg/m^3 and 7ppm for 24 hours respectively. Interventions to improve the indoor air quality in informal settlements should address change in the type of cooking fuels and improvement in the ambient air quality.

Background

Globally, indoor air pollution (IAP) was responsible for 3.8 million death in 2018 [1] contributing to 7.7% of the global mortality [2] and 91.5 million disability-adjusted life years (DALYs)[3] in 2019. It represented the third leading risk factor (6.4% of global DALYs) among children under 5 years, and the second leading risk factor in disease burden for women globally [4]. The public health threat of IAP is highest in low- and middle-income countries where it contributes approximately 10% of mortality [2] resulting in 1000-fold difference with high-income countries[5]. In 2019, household air pollution (HAP) resulted in 697,000 deaths in Africa [6]. In Uganda, IAP has been significantly associated with respiratory tract infections, especially in children [7, 8].

Household air pollution is generated by incomplete combustion of fuels leading to IAP with emission of air pollutants including fine nitrogen dioxide (NO_2), particulate matter (PM) and CO[9, 10] , and is closely linked to the rapid urbanisation and unmitigated household use of solid fuels. The widespread use of solid fuel combustion for cooking and heating energy needs among an estimated 3 billion people in low- and middle-income countries (LMICs) is partly responsible for the increasing levels of household air pollution. Reliance on solid fuels for household energy in LMICs is largely due to limited access (availability and affordability) to cleaner sources of energy such as electricity or liquefied petroleum gas (LPG) [11]. The number of people using solid fuels for household energy needs is expected to increase through 2030, with Sub Saharan Africa projected to have the highest increase in household solid fuel use for cooking.

Available data indicate that 90% of households in Uganda use solid biomass fuel, which elevates the risk of household air pollution [12]. Inhalation of air pollutants such as PM leads to the development of cardiopulmonary illnesses while very high CO exposure is associated with hypoxia that affects organs with high oxygen consumption including the developing fetus [13-15]. Furthermore, exposure to $PM_{2.5}$ and CO is associated with acute lower respiratory infections (ALRI) which are estimated to cause 5,700 deaths in children in Uganda annually [8, 16]. The risk is exacerbated in crowded urban environments such as informal settlements since urban environments are responsible for producing 78% of carbon emissions [17]. Informal settlements are characterised by crowded, dilapidated and unregulated housing structures that generally have poor ventilation, inadequate water, sanitation and hygiene access, limited services and infrastructure, low government response to needs and services [18, 19], lack of planned and allocated cooking areas, other unmitigated sources of air pollution such as open burning of solid wastes [20] and, poor ambient air quality[21]. This leads to the “triple threat” of communicable, non-communicable diseases (NCDs) and injuries in these urban informal settlements. Informal settlements in Uganda are at risk of increased rural-urban migration due to anticipated urbanization of the cities [22] leading to its population growth along with an increase in demand and usage of cooking fuel energy.

To combat air pollution in Uganda, the Ministry of Energy and Mineral Development instituted a Value added tax (VAT) waiver[23] of 17% on low-pressure gas (LPG) and embarked on national grid expansion and reinforcement for electricity[24] to encourage its usage of LPG and electricity for cooking as they are cleaner energies. Additionally, the Ministry of Lands, Housing and Urban Development oversee the physical planning of areas in Uganda and regulate and approve of building plans for each district in an effort to reduce informal settlements and unregulated structures. Despite these measures, IAP is still prevalent [25]. A significant number of studies have been done on IAP in Uganda [26-29]and the associated health effects in rural and formal settings [30-37]. Most studies have looked at environmental risk factors such as exposure levels [38] and health effects of HAP [8, 39, 40]{Rumchev, 2007 #5}, however, few have focused on IAP in households in urban informal settlements. Furthermore, predictors of the levels of concentrations of $PM_{2.5}$ and CO in the cooking and living area of informal dwellings during the cooking time have not been adequately explored and yet, the established IAQ guidelines cater for a 24hr average [11] which includes both cooking and non-cooking time of which IAQ has been found to differ significantly [26]. Therefore, this study aimed to assess household characteristics that predict the concentrations of $PM_{2.5}$ and CO within households in Kisenyi-Mugunu, an informal settlement in the newly created city of Fort Portal city, Uganda.

Methods

Study setting and population

The study was conducted in Kisenyi-Mugunu, an informal settlement in the Western division of Fort Portal City. Fort Portal is the city of Kabarole district, which is located in Western Uganda. Kabarole district has a total population of 469,236. Of this population, 17.1% are children aged 0-4 years. In this district, only 18.3% of the population have access to electricity with 63.1% using kerosene lamps for lighting [41]. Majority of the residents have low-socioeconomic status and rely mostly on charcoal and firewood for cooking fuel. The housing structures in this area are generally informal and unregulated with poor ventilation. There is also poor storage of charcoal which may lead to wetting when it rains, and thus deteriorating its quality and cooking efficiency leading to increased smoke production when burnt [42]. The study population included residents of Kisenyi-Mugunu and the study units were households in Kisenyi-Mugunu, Fort portal.

Study design, sample size and sampling

A cross-sectional study design was used. Data were collected in September 2020. The required sample size was calculated using the Kish Leslie formula for cross-sectional studies [43]. A p-value of 50% was used due to limited evidence on IAQ in households in informal settlements and a 95% level of confidence with a margin of error of 0.05. Substituting into this formula translated to a minimum sample of 385 households. However, 11 households were dropped due to missing air quality measurements leaving us with 374 participant.

With the help of the village chairperson, households in Kisenyi-Mugunu that had children under five years of age were identified and a list of these residents was provided to researchers. Study households were then randomly selected using computer-generated random numbers. Since this research is part of a larger study investigating the health effects of IAP on child respiratory health, inclusion criteria included having a child under five years and caretaker of the child consenting to participate in the study. Exclusion criteria included having a very sick child. Respondent included caretakers of under-fives.

Data collection

After the consenting process, household interviews were conducted using pretested structured questionnaires. Additionally, observation checklists were used to establish the conditions related to cooking inside and around the home and the cooking practices of the household. The data collection tools were developed and validated by experts in air quality, who are based at the Makerere University School of Public Health. Real-time photometric measurement of $PM_{2.5}$ was done using a Multi-purpose Laser Particle detector LKC-1000S+ (Temtop, USA), while real-time measurements of CO were done using EXTECH Carbon Monoxide Meter Model CO15. Callibration of the instruments was done prior to the training and field measurements. In each household, IAQ measurements for both the cooking area and the living space were conducted during the cooking hours between 8:00 am and 6:00 pm. This was after the cooking fuel had been lit and active cooking was taking place. The air samples were taken at 1m above the floor (the approximate breathing zone height of a child under five years) and 1m from the cooking area. (the approximate distance of a child under five years away from the cooking area). The monitors were placed with the air receivers/inlets at least 1.5m away from the windows and the doors because of reduced airflow near surfaces [44]. A one minute average for measurement of indoor air was adapted according to Saad et al., 2017 [45]. One research assistant took the air quality reading, and the data were later entered into Kobo collect form for the corresponding household. This study was performed in the wet season when ambient air pollution is expected to be low [21].

Study variables

The dependent variables were the concentrations of $PM_{2.5}$ and CO. The independent variables included the main type of fuel used for cooking, nature of kitchen ventilation, location of the cooking area, location of the fuel storage area, duration of cooking, usage of damp/wet fuel, and type of cookstove and its state of repair. The main type of cooking fuels included 1) straw/shrubs/grass, 2) wood, 3) charcoal, 4) kerosene, 5) electricity and 6) LPG/cylinder gas was used. For inferential statistics, the main type of cooking fuel was re-categorised into three classes; 1) less polluting fuels (electricity, LPG and kerosene), 2) moderately polluting fuels (charcoal), and 3) highly polluting fuels (wood, straw, shrubs and grass). Adequate ventilation was defined as having two or more ventilation openings so placed as to ensure parallel or cross-ventilation [46]. Therefore cooking and living area with two or more openings were considered to have adequate ventilation.

Quality control, data management and statistical analysis

To enhance data quality, a 2-day training of research assistants by the study investigators was conducted. The pretest fieldwork was conducted in Bwaise II Kawempe division Kampala. This was purposively selected for the pretest because it had similar characteristics (being informal and densely populated) to the study area. Research assistants were asked for feedback about the clarity of the questions and effectiveness of instructions and necessary revisions were made. Data were collected using the KoboCollect mobile application, which was preloaded on mobile smartphones and tablets. Participant responses were entered in an offline Kobo collect form for each household. Data were submitted to a secure online server (www.kobo.humanitarianresponse.info) daily. The investigators conducted daily data quality checks. Only the study investigators had the security key to ensure data security. Data were downloaded into Microsoft Excel 2010 and exported to Stata 14.0 (StataCorp Texas, USA) for statistical analysis. Some participants' responses were dropped due to missing air quality measurements leaving 374 participants. Data were analysed using both descriptive and inferential statistics. For the descriptive statistics, frequencies and cross-tabulations were generated (where appropriate). For the inferential statistics, linear regression was used to derive associations (e.g., β-beta coefficients) between $PM_{2.5}$ and CO concentrations and household characteristicsThe unpaired t-test was used to estimate the statistical significance of differences between $PM_{2.5}$ and CO in the cooking and living area. The concentration of the $PM_{2.5}$ and CO were log-transformed before running regressions for a more near symmetrical distribution. A variable with a *p*-value less than 0.05 was considered significant.

Ethical considerations

Ethical approval for the study was obtained from Makerere University School of Public Health Higher Degrees Research and Ethics Committee (Reg No. 783). The study was also registered with Uganda National Council for Science and Technology (UNCST) (Registration number HS695ES). Administrative clearance was sought from the Kabarole district Local government which presides over the study area. Information sheets and consent forms were available in the local language (Rutooro) or English with details on the purpose of the project, procedures to be followed as well as the risks and benefits of participation. Informed written consent to participate in the study was sought from all study participants and from their legal guardian(s) where appropriate. For illiterate participants, consenting was conducted in the local language (Rutooro) in presence of a witness and confirmed by participant thumb print on the written consent form. The study was carried out in accordance with relevant guidelines and regulations under strict COVID-19 guidelines as provided by the government of Uganda and UNCST .

Results

Socio-demographic characteristics

A total of 374 respondents were interviewed representing a response rate of 97.1%. The mean age of the respondents was 30.22 (SD±0.51), 95% CI [29.21-31.23]. More than half (55.62%, 208/374) had attained post-primary education (Table 1). The households comprised an average of 4 people. The majority of the cooking 90.11% (337/374), was done by the spouse of the household head.

Table 1: Socio-demographic characteristics of respondents of Kisneyi-Mugunu slum, Fort Portal City, Uganda

Variable	Category	Frequency N=374 (%)
Age category	Below 20	43 (11.5)
	21-30	195 (52.14)
	31-40	98 (26.2)
	41-50	21 (5.61)
	Above 50	17 (4.55)
Level of education	No formal education	27 (7.22)
	Primary	139 (37.17)
	Secondary	181 (48.40)
	Tertiary	27 (7.22)
Religion	Anglican	100 (26.74)
	Catholic	157 (41.98)
	Muslim	73 (19.52)
	Pentecostal	31 (8.29)
	Seventh Day Adventist	13 (3.48)
Marital status	Living with partner	168 (44.92)
	Single	134 (35.83)
	Married	60 (16.04)
	Widowed	7 (1.87)
	Divorced	5 (1.34)
Person who usually does the cooking	Spouse of the household head	337 (90.11)
	Another relative	21 (5.61)
	Maid/ House helper	15 (4.01)
	Do not cook at all	1 (0.27)

Cooking characteristics among households

More than three quarters (88.77%, 332/374) of the respondents used charcoal as the main type of fuel while less than 1% used LPG or electricity (Table 2). Respondents, on average, spent USD$0.6 (SD±0.02) on fuel daily. Above half, 51.87% (194/374) found the daily cost of the fuel acceptable while 28.61% (107/374) reported the daily price as not affordable. The households cooked an average of 2 meals a day and about 4.5 hours were spent cooking per day. More than half (63.37%, 237/374) did not have a separate room used as a kitchen (Table 2). Half 51.87% (194/374) did their cooking outdoors while 16.04% (60/374) usually cooked indoors. Cooking in a separate building outside the house was reported by 32.09% (120/374) of the households. Over half 57.23% (190/332) that used charcoal as the main type of fuel reported cooking from outdoors while 93.94% (31/33) of those that used wood reported cooking from a separate building outside the house.

Table 2: Cooking characteristics among households in Mugunu slum, Fort Portal City, Uganda

Variable	Category	Frequency N=374 (%)
The main type of cooking fuel	Charcoal	332 (88.77)
	Electricity	1 (0.27)
	Kerosene	3 (0.80)
	LPG/cylinder gas	2 (0.53)
	Straw/shrubs/grass	3 (0.80)
	Wood	33 (8.82)
Affordability of fuel	Affordable	194 (51.87)
	Not affordable	107 (28.61)
	Very Affordable	73 (19.52)
Separate room as a kitchen	Yes	137 (36.63)
	No	237 (63.37)
Location of cooking area	Inside the house	60 (16.04)
	Outdoors	194 (51.87)
	Separate building	120 (32.09)
Location of kitchen windows	Not close to the main entrance door	278 (74.33)
	Close to the main entrance door	96 (25.67)
Fuel storage area	Inside the house	164 (43.85)
	Outdoors	73 (19.52)
	Separate building	137 (36.63)
Adequacy of cooking area ventilation	Not adequate	149 (39.84)
	Adequate	225 (60.16)
Traditional cook stove	Yes	311 (83.16)
	No	63 (16.84)
State of repair of the traditional stove (n=311)	Good	260 (83.60)
	Not good	51 (16.40)

Improved cook stove	Yes	92 (24.60)
	No	282 (75.40)
State of repair of Improved cook stove (n=92)	Good	83 (90.22)
	Not good	9 (9.78)
Fuel biomass storage area protected from water ((n=368)	Yes	236 (64.13)
	No	132 (35.87)
Fuel biomass damp (n=368)	No	211 (57.34)
	Yes	157 (42.66)

Majority (74.33%, 278/374) of the households did not have a window close to the main entrance door, however, adequate ventilation of the cooking area was observed for 60.16% (225/374) of the households (Table 2). For those who cooked outdoors, the average cooking distance from the house's main entrance was 3.14±0.17 0m. The cooking time in the study was generally between 8:00 Am and 6:00 PM. Traditional portable and lightweight charcoal cookstoves made of metal with a ceramic liner and one fire per pot which are batch-fed were used by majority of households, 83.16% (311/374) and of these, 83.6% (265/311) were in a good work condition. Fuel was stored indoors by almost half (43.85%, 164/374) of the respondents and 36.63% (137/374) stored the fuel in a separate building outside the house. However, only 64.13% (236/368) reported that the biomass fuel was protected from rainwater while 157/368 (42.66%) were found using damp biomass fuel (Table 2).

Predictors of $PM_{2.5}$ and CO concentration

During the cooking time, the mean $PM_{2.5}$ concentrations for the cooking and living area was 175.93±12.49 μg/m^3 and 124.29±7.95 μg/m^3 respectively (Table 3). These concentrations are higher than the WHO air quality guideline of 25μg/m^3 for 24hr. The mean CO concentration during cooking time was 41.22ppm and 15.23ppm for the cooking and living area respectively. This was also above the 24hr WHO air quality guideline of 7ppm however it was below the 87ppm WHO 15 Minute Average. From an unpaired t-test, it was found that there was a statistically significant difference between $PM_{2.5}$ and CO concentration in the cooking and living area ($t=18.14$, $p \leq 0.05$) and ($t=5.77$ $p \leq 0.05$).

Table 3: **Mean concentration of PM2.5 and CO for the cooking and living area in households in Mugunu slum, Fort Portal City, Uganda**

	Cooking area	Living area	Cooking area	Living area
Mean	175.93	124.29	41.22	15.53
Std. Err.	12.49	7.95	3.31	1.70
[95% CI]	151.37 - 200.49	108.66 - 139.92	34.71 - 47.74	12.18 - 18.87

Cooking in a separate building outside the house resulted in the highest pollution with $PM_{2.5}$ and CO of 176.13 μg/m^3 and 46.86ppm, respectively (Table 4). Cooking outdoors also presented high levels of $PM_{2.5}$ (162.58 μg/m^3) and CO (44.37 ppm). Cooking with all fuel types presented with high concentrations of PM2.5 and CO for both the cooking and living areas for this informal settlement (Table 4). In the neighbouring village of Rwengoma, ambient air quality monitors [21] reported an average $PM_{2.5}$ of 69.62 μg/m^3 in the week during which this study air quality measurements were taken.

Table 4: **Distribution of $PM_{2.5}$ and CO by cooking area location in households in Mugunu slum, Fort Portal City, Uganda**

	$PM_{2.5}$ (μg/m^3)	CO (ppm)
Location of cooking area	Mean (SD)	Mean (SD)
Indoors (n=60)	162.58 ± 11.79	44.37 ± 4.57
Outdoors (n=194)	166.66 ± 6.72	39.27 ± 2.49
Separate building outside the house (n=120)	176.13 ± 9.45	46.86 ± 3.12

At multivariate analysis cooking outdooors was associated with a 0.112 increment in $PM_{2.5}$ concentrations in the cooking area ($\beta_{\text{cooking outdoors}}$ = 0.112 [95% CI: -0.069, 1.614; p= 0.033]) (Table 5) Considering majority of households cooked outdoors in this study,further analysis on cooking outdoors revealed that cooking with less polluting and moderately polluting fuel was associated with a 1.77 ($\beta^2_{\text{cooking outside* less polluting}}$ = -1.77(-3.355, -0.186) and 0.934 ($\beta^2_{\text{cooking outside* moderately polluting}}$ = -0.934 (-1.736, -0.133) decrement in $PM_{2.5}$ respectively (Table 5). Cooking with moderately polluting fuel was associated with a 0.719 increment in CO concentrations ($\beta_{\text{moderately polluting}}$ = 0.718 [95% CI: 0.084, 1.352; p= 0.027]) (Table 6) (in the living room.

Table 5: **Adjusted regression coefficient for predictors of $PM_{2.5}$ concentrations in the cooking and living area in households in Mugunu slum, Fort Portal City, Uganda**

Variable	Cooking area		Living area	
	Coefficient (95% CI)	**P-value**	**Coefficient (95% CI)**	**P-value**
Adequate ventilation				
No	ref		ref	
Yes	-0.027(-0.213, 0.159)	0.78	-0.062(-0.224, 0.099)	0.47
Window close to the door				
No	ref		ref	
Yes	0.176 (-0.022, 0.374)	0.08	0.043 (-0.131, 0.215)	0.63
Damp fuel				
No	ref		ref	
Yes	0.112(-0.064, 0.289)	0.21	0.048 (-0.105, 0.202)	0.53
Cooking outside				
No	ref		ref	
Yes	0.112(0.069, 1.614)	*0.03	-0.024 (-0.201, 0.152)	0.76
Type of fuel category				
Less polluting	0.272(-0.800, 1.345)	0.62	0.022(-0.600, 0.645)	0.95
Moderately polluting	-0.377(-1.115, 0.362)	0.32	0.031(-0.217, 0.27	0.81
Highly polluting	ref		ref	
Cooking outside * Type of fuel category				
Less polluting	-1.770(-3.355, -0.186)	*0.03	-	-
Moderately polluting	-0.934 (-1.736, -0.133)	*0.02	-	-

Highly polluting	ref	-	-
*p-value less than 0.05			
Considering a 95% CI, a p-value ≤ 0.05 was considered to be statistically significant in this study			

Table 6: **Adjusted regression coefficient for variables associated with the concentration of CO in the cooking and living area in households in Mugunu slum, Fort Portal City, Uganda**

Variable	Cooking area		Living area	
	Coefficient (95% CI)	P-value	Coefficient (95% CI)	P-value
Adequate ventilation				
No	ref		ref	
Yes	-0.124(-0.479,0 .231)	0.49	-0.258(-0.619, 0.102)	0.16
Window close to the door				
No	ref		ref	
Yes	0.283(-0.086, 0.652)	0.13	-.019(-0.401, 0.363)	0.92
Damp fuel				
No	ref		ref	
Yes	-0.086(-0.421, 0.249)	0.61	-0.0669(-0.402, 0.269)	0.69
Cooking outside				
No	ref		ref	
Yes	0.493(-1.454, 2.441)	0.62	-0.207(-0.596, 0.182)	0.30
Type of fuel category				
Less polluting	1.697(-0.589, 3.982)	0.15	1.314(-0.034, 2.663)	0.06
Moderately polluting	0.427(-1.474, 2.328)	0.66	0.718(0.084, 1.352)	*0.03
Highly polluting	ref		ref	
Cooking outside * Type of fuel category				
Less polluting	-1.608(-5.127, 1.912)	0.37	-	-
Moderately polluting	-0.129(-2.116, 1.858)	0.90	-	-
Highly polluting	ref		-	-
p-value less than 0.05				

Considering a 95% CI, a p-value ≤ 0.05 was considered to be statistically significant in this study

Discussion

This study aimed to assess household characteristics that predict the concentrations of $PM_{2.5}$ and CO within households in an urban informal settlement in the newly created city of Fort Portal city, Uganda. The main type of cooking fuel used by the households was charcoal. The concentration of $PM_{2.5}$ and CO during the cooking time for both the cooking area and the living area were above the WHO Air Quality limits of 25µg/m^3 and 7ppm for 24hr even for those households that used cleaner energy of LPG and electricity. Cooking from outside was associated with higher $PM_{2.5}$ concentrations in the cooking area. However, cooking from outside using LPG and charcoal showed a reduction of $PM_{2.5}$ concentrations compared to highly polluting fuels of wood, and straw/ shrubs and grass. Cooking with charcoal was associated with an increase in CO concentration in the living space.

In this study, charcoal was the main type of fuel used for cooking. Charcoal is a readily available and accessible fuel as this district is surrounded by forests which serve as a source of wood for charcoal burning. Similar studies conducted in informal settings have found a smaller proportion of households using charcoal or wood at household level [47–49], however it was comparable to findings from a nearby city of Mbarara, Uganda and Avenor in Accra Ghana where charcoal was reported to be the most commonly used cooking fuel [38, 50]. Burning of charcoal biomass has environmental and health effects. The demand for charcoal encourages deforestation that destroys habitats of vital ecosystems leading to a reduction in ecosystem services including tourism and leading to climate change. Combustion of charcoal releases particulate matter, volatile organic compounds including $PM_{2.5}$ and CO in the cooking and living area that may exceed the WHO Air Quality limits of 25µg/m^3 for $PM_{2.5}$ and 7ppm for CO for 24hr as was observed in this study.

Households that used less polluting fuels of electricity and LPG also had high mean $PM_{2.5}$ concentrations indoors. This study finding indicates that there is possible migration of $PM_{2.5}$ from neighbouring sources. These may include pits where open burning of garbage is done and garages. The other sources also include proximal households that use solid biomass for cooking. These sources facilitate the migration of $PM_{2.5}$ and CO into households using less polluting fuels [51]. This study finding contradicts that observed in Korogocho and Viwandani informal settlements of Nairobi [47] where usage of LPG and electricity resulted in a reduction in $PM_{2.5}$. Our findings imply that the switch to less polluting fuels has to happen for a significant proportion of the neighbourhood for the protective effect of cleaner energy against $PM_{2.5}$ and CO to be realized.

In this study, the use of moderately polluting fuel (charcoal) was associated with an increase in CO concentration in the living area. Incomplete combustion of charcoal in the traditional cookstove that were used may have resulted from the accumulation of CO in the poorly ventilated living spaces. Other studies have shown an association between charcoal combustion and increased indoor CO [52, 53]. Exposure to indoor CO can result in the accumulation of toxic concentrations with mild and short term exposure resulting into nausea, headaches, dizziness, impaired psychomotor function, loss of balance, fatigue and respiratory symptoms [8, 54, 55] while long term exposure can lead loss of consciousness and death [52].

Outdoor cooking was found to be associated with a 0.112 unit increase in $PM_{2.5}$. Most households cooked from outside to avoid getting smoke inside their houses as they lacked space designated for cooking in their single or double roomed structures. Ambient air currents disperse airborne particles produced when cooking is done outdoors away from the cooking area, however, ambient $PM_{2.5}$ concentration from outdoor activities such as open burning of garbage, dust from the earth pathways and roads and, dispersal from nearby cooking areas which used biomass fuels may have contributed to the $PM_{2.5}$ in the outdoor cooking areas. The cooking location is one of the practices that influence the average concentrations of smoke in the cooking areas [56, 57]. For this study, the positive benefits of cooking outdoors may have been negated by the ambient air $PM_{2.5}$ [58]. Ambient air quality monitors [21] in the neighbouring Rwengoma village reported an average $PM_{2.5}$ of 69.62 μg/m^3 in the week during which this study air quality measurements were taken. However, other studies have observed that outdoor cooking resulted in reduced $PM_{2.5}$ [57]. Our study was conducted in an informal setting while Rosat et. al., (2014) [57] was conducted in a rural village which may have been sparsely populated as compared to the informal settlements that are densely populated with more anthropogenic activities resulting into lower $PM_{2.5}$ in ambient air quality for rural areas.

Cooking with less polluting and moderately polluting fuel was associated with a unit decrease of 1.77 and 0.934 in $PM_{2.5}$ respectively. Despite the increased concentration of $PM_{2.5}$ associated with cooking outdoors in this urban informal settlement, using a less polluting cooking fuel of electricity, LPG, or kerosene or moderately polluting cooking fuel of charcoal resulted in decreased concentrations of $PM_{2.5}$ compared to solid biomass fuels of wood and straw/shrubs/grass. Use of less polluting fuels may have resulted in a higher decrease in $PM_{2.5}$ than moderately polluting fuels because when using traditional cookstoves, incomplete combustion of solid biomass fuels occurs due to difficulty in mixing of the fuel and air during burning unlike for LPG (gas) and kerosene (liquid) leading to release of a significant proportion of products of incomplete combustion $PM_{2.5}$. [10, 59]. The decrease in $PM_{2.5}$ concentration with the type of cooking fuel is similar to a study conducted in rural Malawi that assessed the effect of cooking location and type of cooking fuel on the level of $PM_{2.5}$ [60]. The use of less polluting fuels during outdoor cooking in informal settings may contribute to a reduction in $PM_{2.5}$ in the cooking area further emphasising the need to promote cleaner cooking energy.

This study determined the cooking time $PM_{2.5}$ and CO concentrations of the cooking areas and living areas for a high number of households in this urban informal settlement. The cooking period presents the most eminent danger as it is the time the fuel sources are actively burning with the highest expected concentration of incomplete combustion products of $PM_{2.5}$ and CO. The limitation of this study was limited air quality measuring devices available to use for the large sample size as thus a one-minute measurement was adapted according to Saad et. al. [45].

Conclusions

The mean $PM_{2.5}$ and CO concentrations in cooking and living areas were found to exceed the WHO Air quality limits. Cooking outdoors did not have a protective effect against the $PM_{2.5}$ and cooking with charcoal increased the CO in the living area for this informal settlement. Interventions to improve the indoor air quality in informal settlements need to promote a switch to cleaner cooking energy for all households in the neighbourhood for the benefit of reduction in indoor $PM_{2.5}$ and CO concentrations to be realized.

Abbreviations

ALRI Acute lower respiratory infections

CO Carbon monoxide

DALYs Disability-adjusted life years

HAP Household air pollution

IAP Indoor air pollution

LMICs Low- and middle-income countries

LPG Liquefied petroleum gas

NCDs Non-communicable diseases

NO_2 Nitrogen dioxide

PM Particulate matter

VAT Value added tax

WHO World Health Organization

Declarations

Ethical approval and consent to participate

This study received ethical approval from Makerere University School of Public Health Higher Degrees Research and Ethics Committee and registered with Uganda National Council for Science and Technology (registration number HS695ES.) Administrative clearance was sought from the Kabarole district Local government. Written informed consent was sought from the study participants and from their legal guardian(s) where appropriate. For illiterate participants, consenting was conducted in the local language (Rutooro) in presence of a witness and confirmed by participant thumb print on the written consent form. The study was carried out in accordance with relevant guidelines and regulations under strict COVID-19 guidelines as provided by the government of Uganda and UNCST.

Consent for publication

Not applicable

Availability of data and materials

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors report no conflict of interest, financial or otherwise.

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Authors' contributions

WKK was the principal investigator of this study. She oversaw concept development, proposal development, Ethical approval, and conducting the study; supervised data collection, analyzed the data, and developed the manuscript.

RKM guided in the proposal development and manuscript preparations.

EA guided in the proposal development and manuscript preparations.

STW guided in the proposal development, analysis, and manuscript preparation.

VN guided in the concept development.

TS guided in the proposal development, supervision of data collection, and manuscript preparation.

AN guided in the manuscript development.

ESC gave expert guidance during manuscript development and assisted in acquiring the ambient air quality data.

JCS gave expert guidance during concept development, proposal development, and manuscript development.

JBI gave expert guidance during concept development, proposal development, and manuscript development.

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