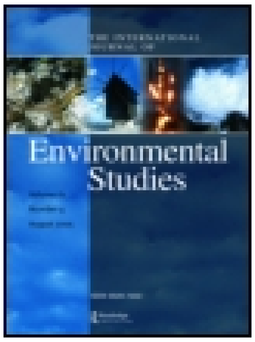

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ARTICLE

Indoor $PM_{2.5}$ characteristics and CO concentration in households using biomass fuel in Kigali, Rwanda

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ABSTRACT

This paper reports the first research investigation in urban Rwanda of indoor $PM_{2.5}$ and CO levels associated with biomass fuel cooking activities. The study included a survey of household and cooking activity among 40 biomass fuel households in Nyarugenge District, Kigali, together with air quality monitoring for particulate matter (PM) and carbon monoxide (CO) within those 20 households in which cooking was performed exclusively indoors. Pollutant concentrations were measured at one-minute intervals, using the IQ Air Visual Pro sensor ($PM_{2.5}$) and electrochemical COA1 (CO) detector adapter devices, respectively. In the majority of households (90%, n = 18) in which monitoring was performed, mean pollutant concentrations were in excess of WHO Air Quality (WHO-AQ) Standards with 24-h values of 93 μgm^3 and 35.1 ppm for $PM_{2.5}$ and CO, respectively. Efforts are required to change household energy policies in favour of cleaner fuel sources and develop effective structural ventilation.

KEYWORDS

$PM_{2.5}$; CO; traditional stoves; biomass; Rwanda

Introduction

Biomass fuels (*charcoal, wood, crop residues and dung)* are used worldwide as the primary source of domestic energy and almost 3 billion people use these as their main source of fuel for cooking [1]. In the developing world, it is estimated that 2 billion people use fuel wood for heating and cooking [2]. Cooking with biomass in traditional cooking stoves produces high levels of toxic pollutants in the kitchen areas.

In poorly ventilated houses, these pollutants cause health problems. These include low birth weight (this increases infant mortality), chronic obstructive pulmonary diseases and acute lower respiratory infections, such as acute bronchitis and bronchiolitis, influenza and pneumonia.

Many researchers [3–9] have mentioned that carbon monoxide (CO) and particulate matter 2.5 ($PM_{2.5}$) come from solid fuel combustion. Because of the small size of $PM_{2.5}$ they can penetrate the deepest parts of lungs and alter the body's defence system, damage lung tissues or aggravate existing lung or

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cardiovascular diseases. Major pollutants are more associated with fuel burning, vehicle emissions and industrial combustion. Studies also show that pregnant women's exposure to the mentioned pollutants can increase the risk of preterm delivery and low birth weight (less than 2500 g) and this contributes to infant mortality and developmental disabilities. Studies in Mexico and India show that the improved cooking stoves reduce the average indoor air concentrations of CO and $PM_{2.5}$ generally by 50% [10,11].

Kalisa et al. have examined this important question in regard to outdoor air pollution in Rwanda [12]. Use of traditional cooking stoves has an impact on human health and on forest area. This is because traditional stoves generally use charcoal, which is produced in rural areas in order to be sold in urban areas. Deforestation is the main cause of land sliding and floods in cities like Kigali in Rwanda. The zones most vulnerable to flooding are the wetland settlements. In recent years, Rwanda has faced a number of natural disasters, i.e. floods and land sliding, in which people have lost their properties and lives. Burning fuel more cleanly by pre-processing might be appropriate, but charcoal production itself is one of the major sources of outdoor air pollution and contributes to deforestation [7]. In addition, charcoal in Rwanda is produced traditionally using kilns and wood cut from forests.

A biomass survey conducted in 2012 by Rwanda's Energy, Water and Sanitation Authority (EWSA) showed that almost all rural households (99.5%) reported using wood fuels as their main source of cooking energy: firewood is predominant in 82.41% of households and charcoal in 14.77%. In Kigali City, the main fuel used for cooking is charcoal (65%) followed by fuel wood (32%). The use of electricity and LPG is still low at 0.9% and 1.4%, respectively. These two fuels are not used because they are very expensive [13].

The researchers found only one peer-reviewed paper on indoor air pollution in Rwanda. This focused on household air pollution in the secondary city of Rubavu [14]. There was also one peer-reviewed paper, on outdoor air pollution [12] with limited 'grey' literature (some of this is cited below) and a few project reports [15–19].

This study aims at measuring CO and $PM_{2.5}$ levels in households cooking with traditional biomass fuel in the City of Kigali, Rwanda.

Material and methods

Settings

This study was conducted in the villages of Kabeza cell in Muhima sector in Kigali City, Rwanda (during July and August of 2018). According to the most recent Population Census in 2012 Muhima sector had a population of 29,768 and the projected growth rate from 2012 was 2.6 per annum [20]; when extrapolated forward to 2018 the population is approximately equal to 33,637. The present study was conducted in households that use biomass-fuelled cooking stoves. Fieldwork was conducted during the dry season, with a temperature range from 15°C to 27°C. In the study area, most of the houses are typically constructed of mud or brick on a timber frame, with an external kitchen. Most of the kitchens have open eaves space (which provides informal ventilation) of different sizes. Figure 1 shows typical kitchens in Muhima sector. All the households in the study area use charcoal cooking stoves. Most of the charcoal cooking stoves in the study area consist of more than one ‘plate’, above which pans are placed (Figure 2). In most households, the stove is usually lit three times each day, to prepare morning breakfast, lunch and dinner.

Figure 1. Typical kitchens in Muhima constructed of mud or brick on a timber frame.

Figure 2. Cooking stove that uses charcoal.

Sampling strategy

In order to choose the sample, two criteria were considered: (i) Households which use a biomass-fuel (charcoal and/or wood) cookstove, (ii) Households with at least one woman aged 18–55 years and which also have at least one child under 5 years [21]. Forty households were randomly selected from the 211 eligible households. The sample size for each village was determined proportionally based on the number of eligible households. The participation rate was 100% with all women approached willing to partake.

In order to make an even choice among the households in all villages, the number of households taken in each village corresponds to the percentage it represents when the total households are considered (see Table 1).

Among these 40 households, only 20 were found to be ineligible (they cook in the kitchens) for indoor air pollution measurements ($PM_{2.5}$ and CO). Of the 40 households selected, the research team identified (by completion of the first stage of data capture) that cooking was performed indoors within 20 households; therefore this subset comprised the final sample for air quality assessment.

Data collection

Data collection comprised two stages. In stage one a standardised household socio-economic characteristics questionnaire was completed by trained surveyors with the respondent being the mother or main caregiver within each household. In stage two, there was indoor air quality monitoring to measure $PM_{2.5}$ and CO concentrations, among households in which cooking was performed indoors.

Household socio-economic characteristics and cooking activity

Data related to demography (age, gender, household composition), socio-economic characteristics (educational level, household income, fuel purchasing behaviour) and cooking activities (kitchen characteristics, fuel type) were obtained using a semi-structured questionnaire. In order to evaluate the sensitivity and local applicability of questions, a pilot study was used among four respondents prior to the survey fieldwork. This questionnaire was administered verbally in Kinyarwanda (the local language), with immediate translation of responses into English at the time of interview. Information collected on cooking activities

Table 1. Households sample selection in all villages of Kabeza Cell, Muhima Sector.

Villages	No. of households	Percentage (%)	No. of households chosen for sampling
Hirwa	30	3	1
Ikaze	211	22	9
Imanzi	105	11	4
Ingenzi	117	12	5
Ituze	173	18	7
Sangwa	160	17	7
Umwezi	154	16	6
Total	950	100	40

included direct observations of kitchen layout, characterisation of main fuel types (charcoal, wood, mixed fuels) and the timing and duration of daily cooking sessions, defined as the period from fire-lighting (start) to fire-extinguishing (end).

The second phase of the study included an assessment of real-time indoor concentrations of CO and $PM_{2.5}$ over a 24-h duration (including cooking and non-cooking times), in the sub-set of 20 households where cooking was identified to be performed indoors. In each study, kitchen monitors were co-located at height 50 cm and distance 100 cm from the cooking stove. All measurements commenced at 08:00 a.m and continued to 09:00 a.m the following day, for a continuous period of approximately 24 h (range 23 to 25 h). Two undergraduate students from the water and environmental engineering programme were trained in how to conduct air quality sampling and both students and Dr Telesphore visited the sampling sites twice per day.

CO levels were measured at one-minute intervals using a battery-powered electrochemical COA1 carbon monoxide detector adapter, with an interval limit of detection (LOD) 0–999 ppm. All measurements were downloaded directly using a mobile phone application, enabling immediate download of stored information after data capture.

Kitchen $PM_{2.5}$ concentrations were measured simultaneously at one-minute intervals using a co-located IQ Air Visual Pro sensor monitoring device (IQAir Company) for approximately 24-h duration (range from 23 to 25 hours). Each sensor was connected to a main electricity supply to ensure that the battery was being recharged and to prevent data loss. $PM_{2.5}$ data were downloaded from the AirVisual Node/Pro's data device using Samba software.

Ethical approval

Ethical approval was obtained from the Comprehensive Mental Health Services (CMHS) Institutional Review Board (IRB) (approval notice No 317/CMHS IRB/2017). All participants were provided with a study information sheet and provided written informed consent at the time of first contact. All participants were compensated for their time and effort through reimbursement of health insurance equal to 9000 Rwandan Francs (RwF) (9 USD) of three family members (mother, father and the participating children), with average payment RwF1000 (1 USD.05) at the first point of contact. Community health mobilisers at the village level were selected to assist with recruitment and fieldwork coordination for the project and their time (25 days) was compensated at a rate of RwF5789 (6 USD.10) per day.

Results

Socio-demographic characteristics of household respondents

A total of 40 household respondents participated in the survey questionnaire. The age of participating mothers ranged between 20 and 47 years, and their children were between 1 month and 23 years. Of the interviewed families 47.5% had two

Table 2. Social demographic and economic characteristics.

Household (n = 40)	Mean ± SD	n (%)
Mothers (n = 40)	32.43 ± 6.55	
Women's Age (years)		
Women's status		
Live with husband		25 (62.5)
Don't live with husband (divorced, widowed and have children but never been married)		15 (37.5)
Education		
University degree (BA Degree)		3 (7.5)
Secondary		10 (25.0)
Primary		25 (62.5)
No education		2 (5.0)
Occupation		
Home		8 (20.0)
Employed		32 (80.0)
Family income		
Low (<100,000 RwF)		19 (47.5)
High (100,000 < ~250,000 RwF)		21 (52.5)
Own the land		
No		34 (85.0)
Yes		6 (15.0)
Own the house		
No		30 (75.0)
Yes		10 (25.0)
Number of children in a family		
0		0 (0.0)
1		7 (17.5)
2		10 (25.0)
3		9 (22.5)
4		4 (10.0)
4<		10 (25.0)

SD = Standard Deviation.

or three children, 17.5% had only one child, and 35% more than three children. Most women (62.5%) had completed primary education (1–6 years of education), 25% had secondary education; only three mothers (7.5%) reported having university degrees and 5% reported to have never attended school. Almost half of the households (47.5%) earned less than RwF100,000 (105 USD.30 per month) and 21 houses (52.5%) earned more than this per month (Table 2).

Table 3 shows characteristics of household, kitchen, stove and fuel. All study households were constructed of mud and bricks, covered with iron sheets. In this convenience sample, almost half of the mothers reported cooking outdoors (n = 19, 47.5%), with cooking performed in an external kitchen in 13 households (32.5%) and within the living room area (with partitioning) in a minority of dwellings (n = 8). Charcoal was the most common cooking fuel used exclusively within 85% of households, with the remainder (15%) using both wood and charcoal. There was variation in cooking patterns and timing of cooking sessions, with the majority of mothers (62.5%) performing two or three daily sessions of cooking and 15 respondents (37.5%) one session only.

Household and kitchen characteristics

Table 3. **Household, fuel and cooking characteristics** (n = 40).

Characteristics	Mean ± SD	n (%)
House: Number of rooms		
1		20 (50.0)
2	1.78 ± 0.92	11 (27.5)
3		7 (17.5)
4		2 (5.0)
4<		0 (0.0)
Number of people living in the house		
<3		1 (2.5)
3		7 (17.5)
4		8 (20.0)
5	5.25 ± 1.89	9 (22.5)
6		4 (10.0)
6<		11 (27.5)
Smoking at house (family member)		
No		37 (92.5)
Yes		3 (7.5)
Fuel and cooking activity		
Cooking place		
Kitchen		13 (32.5)
Living room		8 (20.0)
Outside		19 (47.5)
Window in cooking place (kitchen and living room)		
Yes		8 (38.09)
No		13 (61.9)
Fuel used for cooking		
Charcoal or firewood		6 (15.0)
Charcoal only		34 (85.0)
Daily cooking session		
1		15 (37.5)
2		22 (55.0)
3		3 (7.5)
Monthly fuel cost		
(<5000 RwF)		6 (15.0)
(From 5000 to 9000 RwF)		18 (45.0)
(>9000 RwF)		16 (40.0)
Daily Time spent for cooking (hours)	2.97 ± 1.16	

Indoor air quality: $PM_{2.5}$ and CO levels

Among a sub-sample of 20 households in which cooking was performed, the indoors real-time $PM_{2.5}$ and CO concentrations were monitored for a 24-h duration. $PM_{2.5}$ and CO levels exhibited high variation in magnitude, with one-minute value concentrations in the range 15 to 1604 μgm^3 and 0 to 503 ppm for $PM_{2.5}$ and CO, respectively (Table 4). Overall 24-h average concentrations were 93 μgm^3 ($PM_{2.5}$) and 35.1 ppm (CO), exceeding WHO Air Quality Standards ($PM_{2.5}$: 25μgm^3; CO: 6 ppm) [21; 22].

Differences in average 24-h concentrations were significantly associated with the number of daily cooking sessions (p = 0.03) with the lowest levels associated with once-daily cooking, which were below WHO IAQ values (Table 4). Figure 3(a–c) shows 24-h $PM_{2.5}$ and CO variation of concentration in three households (one with three cooking sessions, one with one cooking session and one with two cooking sessions). Hourly average CO and $PM_{2.5}$ concentrations in households with two cooking sessions were found to be strongly correlated (r = 0.79; p < 0.01).

Table 4. Air quality summary statistics (20 households).

House	$PM_{2.5}$ (μg/m^3) Duration (h)	Mean	Median	SD	Range	CO (ppm) Duration (h)	Arithmetic mean	Median	SD	Range
CF^1	24	111.34	61.3	195.54	16–1601.4	25	20.18	15	39.5	0–329
CF^2	24	420.40	55	628.93	27–1604	24	19.79	42	35.9	0–151
CF^3	23	611.30	112.5	699.66	31–1599.2	24	139.92	39	255.4	0–240
CF^4	24	118.10	55.8	257.75	24–1589.3	23	42.31	25	46.3	0–310
CF^5	24	119.34	57.4	200.56	18–1520.7	24	51.78	33	101.9	0–475
C^1	24	130.77	82.4	192.96	44–1599.8	23	41.44	25	49.2	0–447
C^2	25	64.53	48	75.97	15–982.1	24	6.69	14	16.7	0–98
C^3	24	102.47	43	134.40	24–746.6	25	52.62	11	93.4	0–349
C^4	24	174.59	58.2	297.94	29–602.3	24	9.48	57	19.8	0-93
C^5	24	318.40	87.5	495.88	17–1600.1	23	27.57	69	61.8	0–377
C^6	23	105.99	52	260.70	18–1499.3	24	66.7	50	78.1	0–503
C^7	24	124.82	37	258.72	21–1598.7	24	27.63	71	57.4	0–325
C^8	24	352.23	54	583.07	27–1601.4	24	20.37	25	11.1	0–117
C^9	25	169.80	70.9	353.45	17–1489.7	23	49.83	15	63.1	0–265
C^{10}	24	118.88	56.6	200.71	18–1520.7	24	20.37	14	48.0	0–471
C^{11}	24	245.77	62.1	486.03	25–1478.2	24	13.77	11	23.9	0–112
C^{12}	24	55.93	53	20.77	19–226.3	24	33.6	55	44.2	0–267
C^{13}	25	65.79	54	53.51	29–599.1	25	35.91	36	71.6	0–399
C^{14}	23	168.14	112.9	258.03	30–1478.2	24	47.41	89	94.9	0–369
C^{15}	24	81.51	49	105.06	24–1602.9	24	27.63	74	68.7	0–325

C = Household uses charcoal.
CF = Household uses charcoal or firewood.

Table 5 shows summary $PM_{2.5}$ and CO concentrations for households by fuel type (charcoal or fuelwood, charcoal only). The results show that average $PM_{2.5}$ and CO concentrations are higher in those households using both wood and charcoal fuel ($p < 0.05$) than those using exclusively using charcoal fuel.

Discussion

To the best of our knowledge, this is the first investigation of household characteristics, cooking activity patterns and detailed characterisation of household $PM_{2.5}$ and CO concentrations in urban Rwanda. Therefore, these findings are of significance within a context of widespread reliance upon charcoal and wood as the primary domestic energy sources. This suffices for decision-makers to initiate actions in order to mitigate public health problems resulting from the use of charcoal and wood fuel. It is hoped that this study will contribute to air quality policy disclosure in Rwanda. During this study, we found a mean temperature equal to 23°C and a mean relative humidity of 64.5%.

This study reports the highest average PM2.5 concentration (in an individual household) of 611.3 μg/m^3 and the lowest average PM2.5 concentration of 55.93 μg/m^3 (See Table 4) (in one of the households). The lowest average $PM_{2.5}$ concentration exceeds the WHO Air Quality Guidance of 25 μg/m^3 for household fuel combustion [21]. For CO concentrations, the highest average concentration was found to be 139.92 ppm whereas the lowest average was found to be 6.69 ppm, which is higher than the WHO Air Quality Guidance 24-h exposure guidelines (6 ppm) [22].

During the present study, some households were found to be cooking with both charcoal and charcoal and firewood. For those relying on both charcoal and firewood,

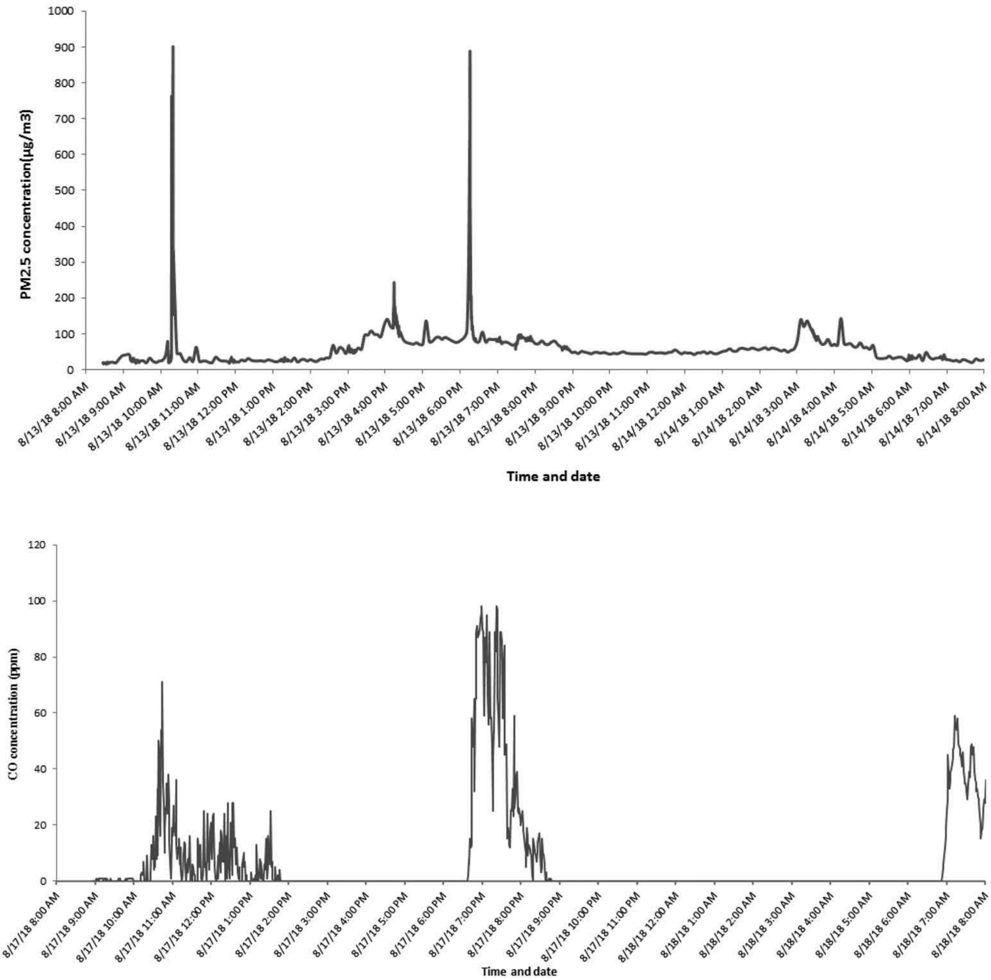


Figure 3. (a). $PM_{2.5}$ and CO concentrations (13–14 August 2018) in the households with three cooking sessions. (b) $PM_{2.5}$ and CO concentrations (15–16 August 2018) in the households with one cooking session. (c) $PM_{2.5}$ and CO concentrations (17–18 August 2018) in the households with two cooking sessions.

average $PM_{2.5}$ and CO concentrations were found to be 276.1 and 54.4 ppm, respectively, whereas the corresponding average $PM_{2.5}$ and CO concentrations in households relying only on charcoal were found to be low (151.97 μg/m^3 for $PM_{2.5}$ and 34.8 ppm for CO). These findings are consistent with those observed for simultaneous use of different cooking fuels reported previously [21,23–25] or may represent differences in moisture content of the respective fuels.

For 20% (refer to Table 4) of the study households, the $PM_{2.5}$ concentrations (24-h average exposure) were greater than 10 times the WHO guidelines.

In all studied households, the contribution to the 24-h average exposure (for both $PM_{2.5}$ and CO) was greater than the World Health Organisation (WHO) guidelines. $PM_{2.5}$ and CO concentrations found in our study are consistent with the average concentrations reported in previous studies conducted in other low-income countries [26–30].

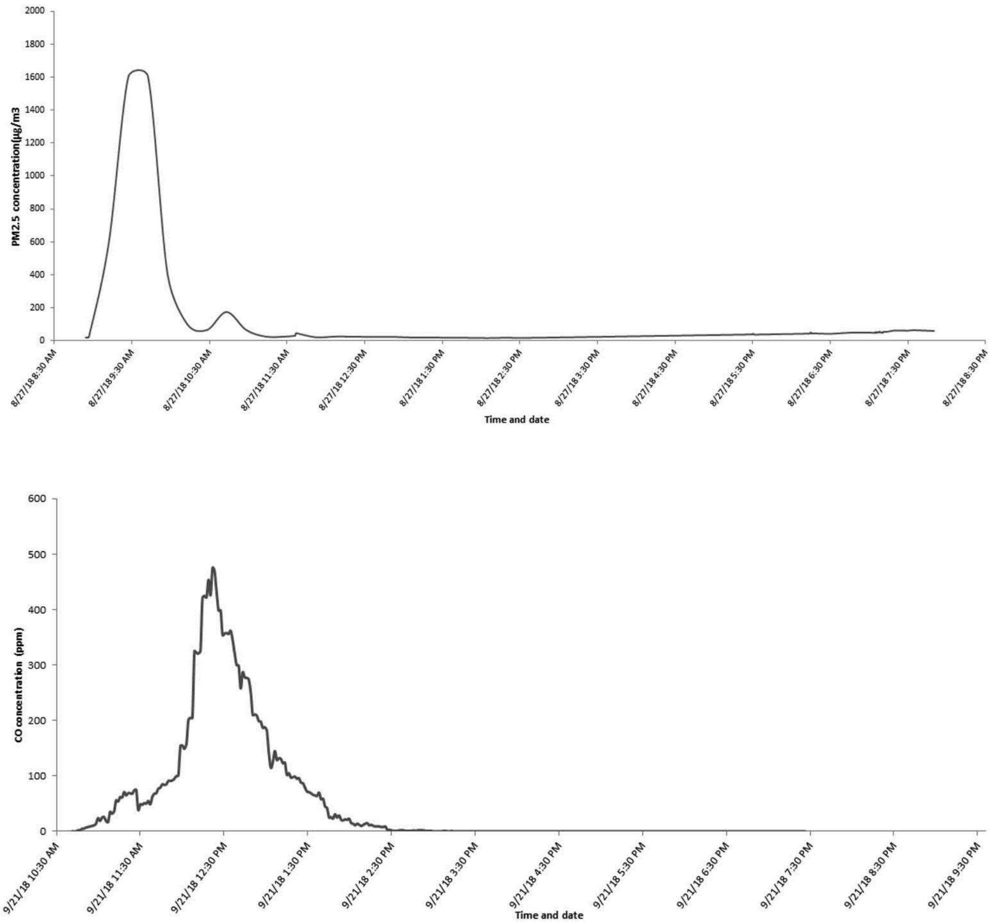


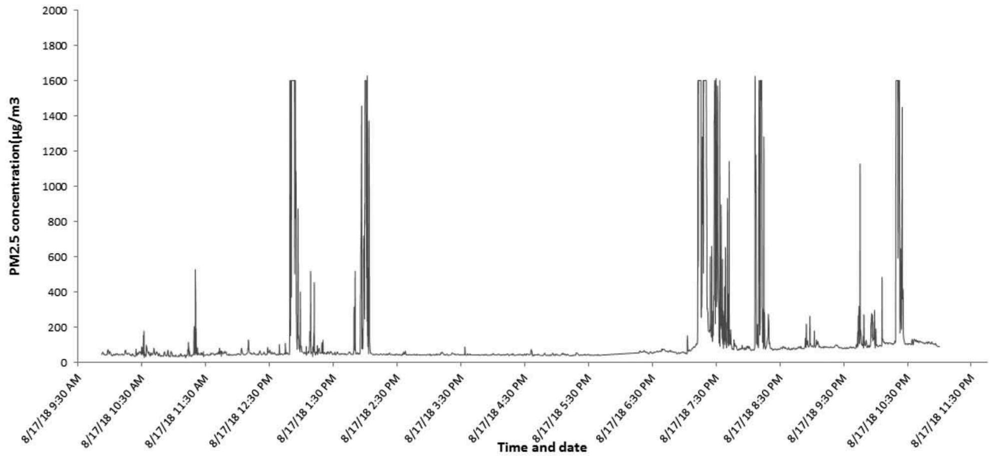
Figure 3. (Continued).

The survey shows that many of the houses possessed rooms with no windows and were relying on a door to vent indoor emissions. The particulate matter can accumulate in a room when there is no cross-exchange of air inside the room. There are health risks because the particulate matter can be inhaled, penetrating the lungs [31–33].

Conclusions and recommendations

This paper has presented CO and $PM_{2.5}$ levels measured from households cooking with solid fuels (biomass fuel and coal) in the City of Kigali. All hourly levels of CO and $PM_{2.5}$ were found to be above WHO Air Quality standards but when mean levels were obtained, 10% of households (two households) had CO mean levels below WHO Air Quality standards. This might be explained by the fact that preparation of meals is done once a day in these households.

The study showed that 75% of the studied households use charcoal only whereas the remaining 25% use both wood fuel and charcoal when cooking. $PM_{2.5}$ and CO



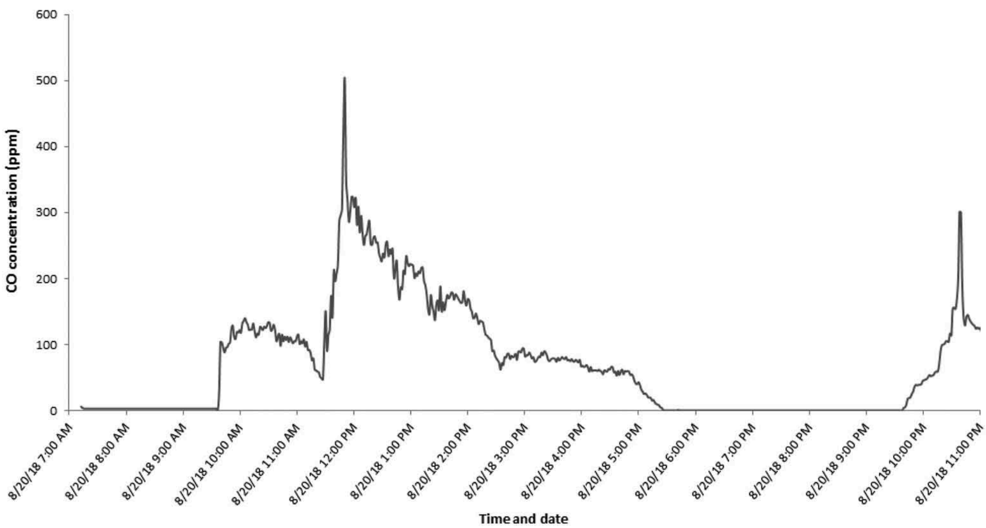


Figure 3. (Continued).

Table 5. $PM_{2.5}$ and CO concentrations for households using charcoal and firewood simultaneously and ones using only charcoal.

Cooking fuel	$PM_{2.5}$ mean level (μg/m^3)	CO mean level (ppm)
Charcoal or firewood	276.1	54.8
Charcoal only	151.97	34.8

measurements were found to be high in the households which use both wood fuel and charcoal when cooking.

The present study is the first of its kind. It concludes that people of Kigali who cook using charcoal and/or wood are exposed to high levels of CO and $PM_{2.5}$ and this exposure can cause adverse health problems such as cardiovascular disease, lung cancer, respiratory infections and strokes [34].

Based on the above findings, this research recommends the following:

(1) A quick change in kitchen design, i.e. improves ventilation by installing a chimney, enlarge the space between walls and roofs, and enlarge windows;
(2) Put in place a household energy policy which prioritises the use of clean fuels;
(3) Awareness campaigns: during our study, we realised that because of the level of education in studied households, household members were not aware of the risks associated with the use of wood and/or charcoal in cooking activities. Therefore, awareness campaigns should solve this problem so that mothers will not expose their children to this harmful fine particulate matter.

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Disclosure Statement

No potential conflict of interest was reported by the authors.

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