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Impact of Improved Cookstoves on the Level of Household Exposure to CO and $PM_{2.5}$ in Sub-Saharan Cities: The Case of the City of Ouagadougou

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Abstract

Air pollution is one of the major global threats to human health. In Burkina Faso, more than 80% of the population uses solid fuels as the main source of cooking energy. This paper reports a comparative study on the exposure of household to the carbon monoxide (CO) and particulate matter ($PM_{2.5}$) emitted by improved cookstoves (ICS) or traditional cookstoves (TCS). A cross-sectional study was conducted in the city of Ouagadougou for 4 months during the rainy season (July to October) in households with an outdoor kitchen. The investigation involved 92 households where air pollutants, such as $PM_{2.5}$ and CO were measured with Indoor Air Pollution Meters (IAP meter). These measurements were focused on the concentration levels of the pollutants during cooking. The results of this study show high levels of $PM_{2.5}$ and CO for all type of stoves. Wood stoves led to higher $PM_{2.5}$ and lower CO emissions than charcoal stoves. ICS reduce emissions of indoor air pollutants compared to TCS. This reduction raised up to 82% for $PM_{2.5}$ and 37% for CO. The analysis of the data measured with the student test (t-test) shows that there is a statistically significant difference between the average values of the concentrations of the pollutants emitted with the TCS compared to ICS, except for CO emissions measured on multi-pot sizes cookstoves (MM). This study shows that the concentrations of indoor air pollutants are very high regardless of the type of cookstoves used. The CO exposure obtained varies from 119.10 to 362.72 μg/m^3 for 15-minute and 10.83 - 55.11 μg/m^3 for 1-hour exposure. The exposure in $PM_{2.5}$ varies from 4762 to 16,257 μg/m^3 for 15-minute and 106.63 to 1597 μg/m^3 for 1-hour of exposure. It was noted that the CO exposure levels obtained over 15-minute of exposure are 1.36 to 4.15 times higher than the WHO recommendation and 1.8 times higher for an exposure time of one hour. This means that women in charge of cooking have a high risk of exposure to air pollutants.

Keywords

Biomass, Cookstove, Particulate Matters, Carbon Monoxide

1. Introduction

Air pollution is a significant environmental hazard to human health. World Health Organization (WHO) reported in 2016, that more than 4.2 million people across cities as well as rural areas, worldwide, died of outdoor air pollution [1]. Two categories namely outdoor and indoor air pollution are in general considered. The outdoor air is influenced by road traffic, and particles from unpaved roads; while indoor air is primarily polluted by solid fuel combustion and smoke from tobacco [2]. In Africa, unpaved road dust, sand winds, industries, urban transport, biomass burning in households and bushfires are the main causes of air pollution [3]-[8]. There are more studies on outdoor than indoor air pollution, however it is important to recognize that we spend most of our time inside buildings. This habit is common in low- and middle-income countries. People exposed to indoor air pollution are particularly women who are involved in cooking and often children while staying with their mothers in the kitchen [9] [10] [11], ([12], p. 200). The concentration levels of indoor air pollutants in kitchens are influenced by several factors, including the type of fuel, the type of cookstove, the method of cooking and the characteristics of the kitchen [13] [14] [15] [16]. Solid fuels are generally used under inefficient conditions causing their incomplete combustion and the increased production of pollutants such as $PM_{2.5}$ and CO [17] [18]. An overview of the literature shows that significant consideration is being given to lowering indoor air pollution through the introduction of more efficient and improved cookstoves [19] [20] [21].

There are few works on indoor air pollution related to cookstove and fuel use in Burkina Faso. Previous studies have focused on the nature of the cookstoves and fuels used by the households, whereby other parameters like kitchen characteristics, nature of fuel, specific measurements during cooking hours and reduction of the outdoor air influence are important parameters in the indoor air pollution study. However, these studies show the influence of the type of cookstove on indoor air pollutant emissions. As an illustration, some studies, in the cities of Ouagadougou and Nouna in Burkina Faso have shown that cookstove type, and fuel type influence emissions of indoor air pollutants [22] [23].

ICS were designed to increase energy efficiency and reduce air pollutant emissions. Laboratory measurements on “Roumdé” cookstoves, an ICS, commonly found in Burkina Faso show a wood saving of more than 40% compared to TCS

[24]. Unfortunately, several studies have highlighted the inefficiency of this technology regarding its performance in reducing pollutant emissions [25] [26].

Despite the good performance of ICS, they remain sources of pollution that can damage populations' health. Also, it is important to investigate whether this technology is able to produce pollutant emissions that are statistically significant different from those of TCS.

In light of the above, we conducted a study in some households in the city of Ouagadougou, which aims to evaluate the concentration levels of pollutants ($PM_{2.5}$ and CO) emitted during cooking activities, to highlight the contribution of different cookstoves to indoor air pollution. A cross sectional method, according to the method of assessment of cookstove performance, is used in order to characterize the households through a survey that will highlight information about the households' characteristics and their energy habits, and then to measure the pollutant concentrations inside the kitchens, taking into account the type of cookstoves and fuel used. This will also allow to assess the level of vulnerability of people in charge of kitchen, to indoor air pollutants.

2. Materials and Methods

2.1. Study Area

The study area is located inside Ouagadougou, Capital of Burkina Faso, Western Africa. The sector 15 that is the subject of our study is located in the northwest of the city of Ouagadougou at 12˚23'44" north latitude and 1˚35'18" west longitude. Its average altitude is 300 meters. **Figure 1** represents the map of the different locations representing the households involved in this study. With a population of 2.5 million in 2015, the population of Ouagadougou has increased to 2.78 million in 2020.

2.2. Materials

2.2.1. IAP Meter

The IAP meter is a device used to measure the concentration of indoor air pollutants such as CO and $PM_{2.5}$. There are mainly three contexts in which this device can be used: Laboratory Study with Water Boiling Test (WBT), Field study with the controlled cooking test (CCT), Population exposure monitoring.

The IAP meter has two sensors that are used to measure the concentration of $PM_{2.5}$ and CO in a location.

The measurement data are directly processed in an excel software. The software analyzes the data and gives the average concentrations of the measured pollutants during operation, and also the highest average concentrations over a 15-minute period. It also provides the results in graphical and tabular form.

2.2.2. Cookstoves and Fuels Used by Households

The most common cookstoves used in the city of Ouagadougou are classified into three groups, namely: traditional cookstoves, improved cookstoves (multi pot sizes cookstove, Ouaga métallique cookstove and Burkina mixte cookstove)

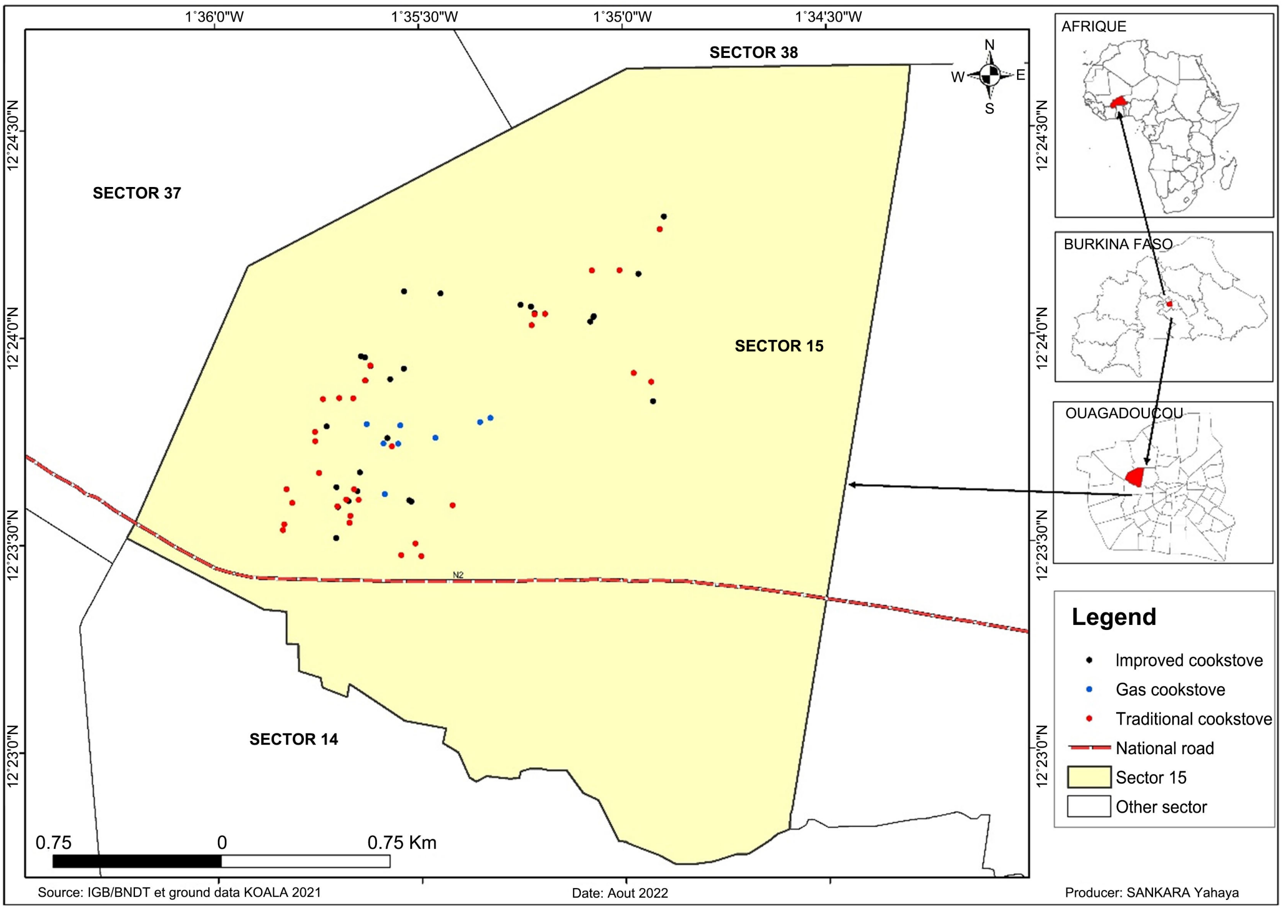

Figure 1. Map and location of the households studied of sector 15 of the city of Ouagadougou.

and gas cookstoves, while the type of cooking fuel included wood, charcoal and butane gas (**Figure 2**).

2.2.3. Material for Measurement of Fuels Parameters

Two devices were used to determine the main fuels parameters for this study: A hygrometer (range of 0% to 60% moisture with an accuracy of 1%) and a scale.

2.3. Method

2.3.1. Sampling

In this section, in addition to giving an overview of the different sampling methods that are used for cookstove performance studies, we define our sample size based on one of the most appropriate methods for our case study.

There are three study methods available for the performance analysis of improved cookstoves versus traditional cookstoves and their emissions: Cross sectional, before and after, before and after with control group [27]. In this study, we refer to the cross-sectional method that is the most appropriate, given the advantages that it offers.

In order to estimate the sample size, the coefficient of variation (COV) and the detectable difference in means (DDM) of the emissions of ICS compared to

(a) (b) (c) (d)

(e) (f) (g)

Figure 2. Cookstoves used by households in the city of Ouagadougou. (a) Traditionnal metallic cookstove (malgasian wood cookstove); (b) Tradiational Three-stone cookstove; (c) Traditionnal metallic coostove (malgasian charcoal stove); (d) Multipot sizes cookstove; (e) Ouaga métallique cookstove; (f) Burkina mixte cookstove; (g) Faitout Gas cookstove.

TCS are evaluated based on the preliminary tests conducted in laboratory using the Laboratory Emissions Measurement Test (LEMS). The results indicated COV values varies from 40% to 80% and a DDM of about 50% to 65%. Thus 80% and 50% were considered for COV and DDM respectively in this study; these values are those expected at the end of the study. From Table 1 which gives the sample size according to the two parameters, a sample of 40 households per type of cookstove and a total sample of 80 households were defined.

2.3.2. Household Selection

This study focuses on households with an outdoor kitchen. This choice makes it possible to consider the pollution from the cookstoves without the influence of other sources. It also focused on the most used cookstoves (traditional, improved and gas) and fuels (wood, charcoal and gas) in the city of Ouagadougou.

Households that met the requirements of the study were selected first and then they consent to participate to the survey and measurements over a period of three days were required for each household.

2.3.3. Kitchen Performance Test

The method defined for the study of the performance of the cookstoves to evaluate the quantities of fuel used by the households and their humidity before the cooking activities is summarized as follows: before the day of the measurement, each household is advised to collect the amount of fuel that will be used throughout the day after. This fuel is weighed early in the morning before using and in the evening after the last cooking activity in order to assess the amount of fuel used. The moisture content of the fuel is also measured on samples collected and oven

Table 1. Sample size needed in each group in cross-sectional studies to evaluate improved versus traditional cookstoves [27].

		COV of measurements												
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3
Detectable difference in means	10%	16	63	142	251	393	565	769	1005	1272	1570	1900	2261	2653
	20%	4	16	36	63	98	142	193	251	318	393	475	565	663
	30%	2	7	16	21	44	63	86	112	142	175	211	251	295
	40%	1	4	9	16	25	36	48	63	80	98	119	142	166
	50%	1	3	6	10	16	23	31	40	51	63	76	91	106
	60%	1	2	4	7	11	16	22	28	36	44	53	63	74
	70%	1	2	3	5	8	12	16	21	26	32	39	46	54
	80%	0	1	2	4	6	9	12	16	20	25	30	36	42
	90%	0	1	2	3	5	7	10	13	16	20	24	28	33
	100%	0	1	2	3	4	6	8	10	13	16	19	23	27

dried. Each measurement is repeated at least three times with each fuel to obtain an average value [28].

2.3.4. Measurement of Air Pollutants

The measurement of air pollutants was carried out with the same type of device (IAP Meter) in all households. This device has been used in several studies related to indoor air pollution from cookstove use [29] [30]. When the sampling tube is connected to the IAP meter, it is possible to measure the exposure to pollutants in the kitchen and the concentration of indoor air pollutants. The different CO and $PM_{2.5}$ sensors of the device allow to sample these pollutants during the cooking period.

The device was run according to the protocol defined for its use. It was therefore placed at 1.4 m from the cookstove and at a height of 1.4 m as shown in **Figure 3**.

The devices in each household were set up early in the morning (around 7:30 am) before the start of cooking activities and removed in the evening after the last cooking activity (around 7:00 pm). Periodic maintenance was done on the device to avoid particle deposits and to ensure the effectiveness of the measurements.

2.3.5. Data Analysis Method

Descriptive analysis was used to determine the average levels of pollution observed for each type of fuel and cookstove. It also allows for a comparative study of the emissions of the different cookstoves used by households by observing the averages and calculating the rates of reduction of emissions from improved cookstoves compared to traditional cookstoves.

The analysis allowed the calculation of the mean, standard deviation, distribution and median for the pollutants concentrations of the different types of cookstoves.

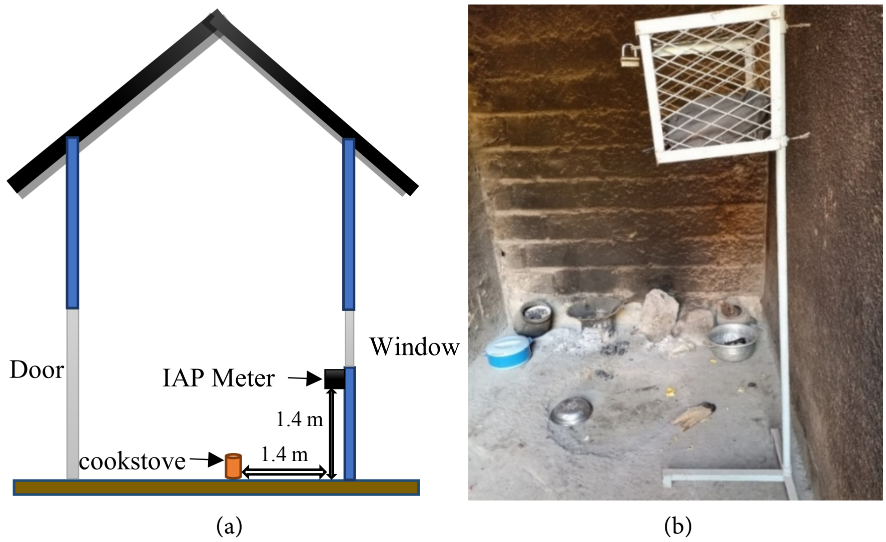

Figure 3. Location of the IAP Meter in a kitchen. (a) Illustrative image; (b) Real picture.

The Student's t-test was used to evaluate the pollution levels and to show whether or not there was a statistically significant difference between the emission data of the different cookstoves and fuels. This test is chosen considering that the values of the emissions that were obtained in this study do not follow a normal distribution. It is carried out using the Stata software.

3. Results and Discussion

The data presented in this section are those extracted from the IAP meter. The aim is to evaluate level of pollution in households for eventual comparison pollution associated to the cooking stove facilities. For wood fuel, the reference stove is the 3 Stones stove, and for charcoal the reference is the so called Malagasian charcoal stove.

3.1. Descriptive Analysis

3.1.1. Indoor Pollutants Concentrations in Kitchens: A Comparative Analysis

The boxplot of **Figure 4** shows the minimum values, first quartiles, medians (central dark line), third quartiles and outliers of the distribution of the mean concentration of pollutants measured.

It gives the evolution of pollutants mean concentrations measured during 15 minutes (PM_15 min and CO_15 min), one hour (PM_60 min and CO_60 min) and during the entire cooking activity (PM and CO) inside the cooking area as a function of time, type of fuel and type of cookstove.

Cookstoves (BM for Burkina mixte cookstove, MM for Multi pot size cookstove and TCS for Traditionnal cookstove) involving wood are denoted BM_w, MM_w and TCS_w, while those involving charcoal are denoted BM_c, MM_c and TCS_c.

The results show that higher particulate matter emissions are caused by wood

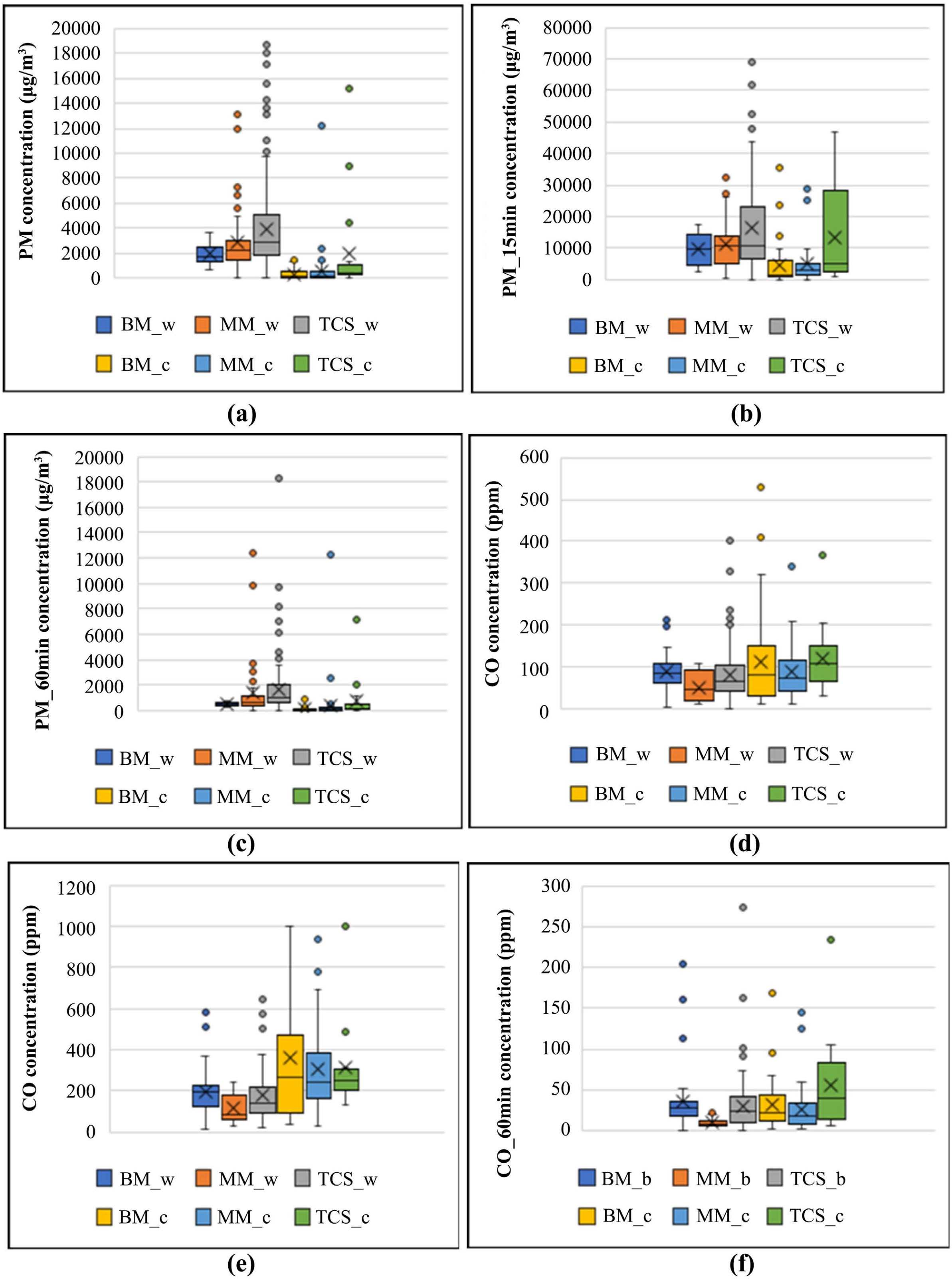

Figure 4. Whisker box plots showing PM and CO mean concentration distribution. (a), (b) and (c) represent the PM concentrations measured over cooking activity, 15 min and 1 hour respectively. (d), (e) and (f) represent the CO concentrations measured over cooking activity, 15 min and 1 hour respectively. (a) PM; (b) PM_15 min; (c) PM_60 min; (d) CO; (e) CO_15 min; (f) CO_60 min.

use compared to charcoal use with both traditional and improved stoves (MM, BM). This could be related to the fact that wood contains more volatile compounds, responsible to the larger smoke release compared to the charcoal combustion.

The PM concentrations are higher at the beginning of the cooking process (15 min) in the same order of the above-mentioned types of cookstoves. This is partly due to the design of the cookstoves used. The TCS exposes the fuel to a high air richness, which causes a turbulent combustion with a high emission of unburnt particles (PM). The combustion of the wood takes place with a lower air richness in the ICS (MM and BM) than in the TCS cookstove. Similarly, BM cookstove cause more CO emissions than the TCS. This is due to low oxygen during combustion. Also, it could be noticed that the BM cookstoves confine more fuel during the combustion than the MM ones. This causes a pronounced lack of oxidant during combustion in BM compared to the MM cookstoves. As a result, they cause more CO emissions during the whole cooking activities.

The concentrations of PM, (PM_15 min and PM) in the traditional cookstoves are higher than those observed in the MM cookstoves and the BM cookstoves. The results of the concentrations of CO, CO_15 min and CO_60 min measurement indicate that the use of BM cookstoves presents more emissions of CO than TCS and MM cookstoves.

TCS produce more PM (1961 $\mu g/m^3$ versus a range of 351 to 615 $\mu g/m^3$ for ICS) than ICS during charcoal use but with lower magnitudes. The large amount of smoke observed may result from poor combustion of wood compared to the charcoal. Similarly, the emitted CO ranges from 88.66 to 111.23 ppm in ICS versus 121.22 ppm in TCS with charcoal. These trends can be explained by the low air supply in ICS where the airflow is associated to the configuration and shape of the kitchen.

Figures 4(a)-(f) show that the fuel has a very significant contribution on the air pollutant emissions. It was noted that all cookstoves emit more CO when fueled with charcoal (88.66 to 121.22 ppm) than wood (50.94 to 90.42 ppm). This is due to the fact that charcoal combustion involves more carbon oxidation to carbon monoxide. The carbonization reduces wood volatile matter to give only a final product (charcoal) that has a high content of fixed carbon. CO comes from incomplete combustion, and will therefore be more abundant in charcoal combustion than in wood. These results are in agreement with those of Bhattacharya *et al.* who showed that emissions of CO and CO_2 pollutants are significant during charcoal combustion more than wood combustion. The CO emission factors range from 19 to 136 g/kg and 35 to 198 g/kg for wood and charcoal respectively [18].

3.1.2. Emission Reduction Rate

Table 2 shows the emission reduction rates of improved cookstoves compared to the traditional cookstoves that are the reference.

For wood fuel use, the use of MM and BM cookstoves lead to a reduction of

Table 2. Percentage reduction in pollutants emissions.

	$PM_{2.5}$ (µg/m³)			CO (ppm)		
	Mean	σ	Reduction rate (%)	Mean	σ	Reduction rate (%)
Wood						
TCS	Ref.	Ref.		Ref.	Ref.	
MM	2878.87	2690.97	27.57%	50.936	33.10	33.72%
BM	1992.09	906.07	49.88%	90.42	52.62	−10.56%
Charcoal						
TCS	Ref.	Ref.		Ref.	Ref.	
MM	614.91	1661.38	68.65%	88.66	63.24	26.86%
BM	350.95	471.06	82.11%	111.23	114.42	8.24%

σ: standard deviation and Ref: average concentration in TCS.

PM concentrations in the order of 27.57% and 49.88% respectively. However, BM cookstoves increase the CO concentration level by 10.56% due to insufficient air during combustion and MM cookstoves reduce the concentration level by 33.72%.

When charcoal is used as fuel, the PM concentration reduction rates for MM and BM cookstoves are in the order of 68.65% and 82.11% respectively. In regard to CO concentrations, the MM cookstoves reduce the concentration by 26.86% and the BM cookstoves by 8.24%.

These results of emission reduction are consistent with the work of Deepthi *et al.* who found in their study that in terms of PM and CO emission, the reduction rates ranged from 20% to 80% and 12% to 93% respectively [31].

3.2. Comparative Analysis with the Student Test

Table 3 presents the results of the statistical analysis on the measured data.

Considering $PM_{2.5}$ concentrations, significant differences are noted in the following groups of cookstoves: BM-MM, BM-TCS and TCS-MM when wood is used with a p-value less than 5% and BM-TCS, TCS-MM with an acceptable p-value at the 10% threshold for charcoal.

With respect to the concentrations of CO emissions, significant differences are observed in the following groups of cookstoves: BM-MM and BM-TCS for the use of wood and TCS-MM for charcoal with p-value lower than 5%.

In general, the use of TCS lead to more pollutant emissions than ICS except for the MM cookstoves where the CO emissions do not show a statistically significant difference compared to the TCS CO emissions.

3.3. Comparison with Similar Studies

Table 4 and Table 5 report the results of the present work for improved and traditional cookstoves respectively with those of other studies conducted under similar conditions.

Table 3. Results of t-test analysis with unequal variance.

Pollutants	Fuels	cookstoves to compare	P-value	t-test results
PM	Wood	BM – MM	0.0392	Ha
		BM – TCS	0.0000	Ha
		TCS – MM	0.0144	Ha
	Charcoal	BM – MM	0.1335	H0
		BM – TCS	0.0518	Ha at the 10% threshold
		TCS – MM	0.088	Ha at the 10% threshold
CO	Wood	BM – MM	0.0025	Ha
		BM – TCS	0.0072	Ha
		TCS – MM	0.1836	H0
	Charcoal	BM – MM	0.1295	H0
		BM – TCS	0.3479	H0
		TCS – MM	0.0576	Ha

Ha: We can see that the mean values are statistically different from each other and H0: We find no statistically significant difference in the means.

Table 4. Results of measurements from ICS.

ICS	$PM_{2.5}$ (ug/m^3)	CO (ppm)
	Mean (σ)	Mean (σ)
This study	2690.89 ± 2523.90	82.32 ± 52.70
Grabow *et al.*, 2013	973 ± 116	31 ± 10
De la Sota *et al.*, 2018	4621.9	23.8
Muralidharan *et al.*, 2015	714	12.7
McCracken *et al.*, 1998	450 ± 550	11.92 ± 18.16

Table 5. Results of measurements from TCS.

TCS	$PM_{2.5}$ (ug/m^3)	CO (ppm)
	Mean (σ)	Mean (σ)
This study	3974.65 ± 3479.04	81.78 ± 65.55
Grabow *et al.*, 2013	1145 ± 2030	43 ± 71
De la Sota *et al.*, 2018	10563.9	41.3
Bartington *et al.*, 2017	1037	7.1
Deepthi *et al.*, 2019	1481	-
Nayek and Padhy *et al.*, 2018	2055.76	-
Muralidharan *et al.*, 2015	916	16
McCracken *et al.*, 1998	27,200 ± 13,600	94.4 ± 24.96

σ: standard deviation.

It should be noted that the results of the present work are in the same order of magnitude as those of De la Sota *et al.* with respect to ICS for both types of pollutants studied ($PM_{2.5}$ and CO). For TCS they are in the same orders of magnitude as some studies [14] [29] [32] [33]. However, it should be noted that the present results are largely high in comparison to most other results found in the literature. This could be due to the combustion conditions (fuel filling rate), the quality of the fuel (moisture, volatile matter content…) and the configuration of the ICS, which imposes a difference in the air richness during the combustion process [13] [33] [34].

3.4. Level of Risk from Exposure to Pollutants

Indoor air pollutants, emitted during cooking activities, are a major health risk to the populations exposed to them. Several studies have shown the risk of exposure to these pollutants in the short and long term. This highlights that exposure may be the cause of some of the diseases that affect physical health such as hypertension, cancer and other respiratory diseases (persistent cough and asthma) [35]-[40].

The pollutants most considered to be a significant public health risk are fine particulate matter ($PM_{2.5}$) and gases (CO, ozone, sulfur dioxide, nitrogen oxides and volatile organic compounds) [41].

To deal with this problem, the WHO has defined guidelines in an order to preserve the populations' health. The standards defined include several indoor air pollutants such as $PM_{2.5}$ and CO which were the focus of our current study. The guide values presented in **Table 6** below show a comparison of the exposure levels obtained in this study to the WHO air quality guidelines.

This study gives the average concentration values of CO which are between 119.104 and 362.715 ppm for 15 min exposure period and between 10.832 and 55.113 ppm for a one-hour exposure period. These values are 1.36 to 4.15 more than the 15 min guideline which highlights the hazardous exposure of some households. For the one-hour exposure, some households are exposed to a risk level below the average concentration and others have an exposure risk level that may be 1.8 higher than the recommended limit value.

Table 6. Comparison of the exposure level obtained in the present study to the WHO air quality guidelines.

Pollutant	Averaging time	recommended level µg/m³ (ppm*)	Level of pollution obtained in this study (ppm)
$PM_{2.5}$	Annual	5	-
	24-hour	15	-
CO	24-hour	4000 (3.49)	-
	8-hour	10,000 (8.73)	-
	1-hour	35,000 (30.55)	10.83 - 55.11
	15-minute	100,000 (87.3)	119.10 - 362.72

*1 ppm = 1.145 mg/m³.

But in summary, we can note that women in charge of cooking in households are highly exposed to a critical level of indoor air pollutants that can affect their well-being. This is due to the fact that the person in charge of the kitchen is often obliged to stay inside the cooking area for a period sometimes longer than 15 minutes to control the meal, which induces an exposure to CO. This exposure has drawbacks for the pregnant woman which can be the cause of a low birth weight [42] [43] [44]. It can also be responsible for fatigue, headache, malaise and concentration deficiencies in adults [45] [46].

4. Conclusion

Solid fuels are the primary energy sources used by households for cooking, but also remain important factors in indoor air pollution. It is also recognized that the type of cookstove used for cooking activities is a factor that contributes to increased pollutant emissions. In this study, we carried out measurements of air pollutants ($PM_{2.5}$ and CO) in 41 households that use TCS, 41 households that use ICS. The objective was to show how the types of cookstoves and the nature of the fuel can impact the indoor air pollutant concentration levels in households in the city of Ouagadougou. The results showed that wood burning generates more $PM_{2.5}$ and less CO than charcoal. Also, ICS such as MM and BM give a reduction in emissions of $PM_{2.5}$ ranging from 27.57% to 82.11% and a reduction in CO that can reach 37.72% compared to TCS. But in an overview, the average concentrations of $PM_{2.5}$ and CO from TCS are statistically significantly different from those of BM cookstoves. However, CO concentrations, from the use of TCS do not give a statistically significant difference compared to those from MM cookstoves. In the next steps of this work, it is planned to carry out emission measurements in the laboratory with the water boiling test method using the same types of fuels and cookstoves encountered in this study. This will allow us to provide more efficient measurement data in a well-controlled environment.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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