Assessment of Indoor Air Quality of Porous Media Combustion Based Cookstoves

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Research Article

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Assessment of Indoor Air Quality of Porous Media Combustion Based Cookstoves

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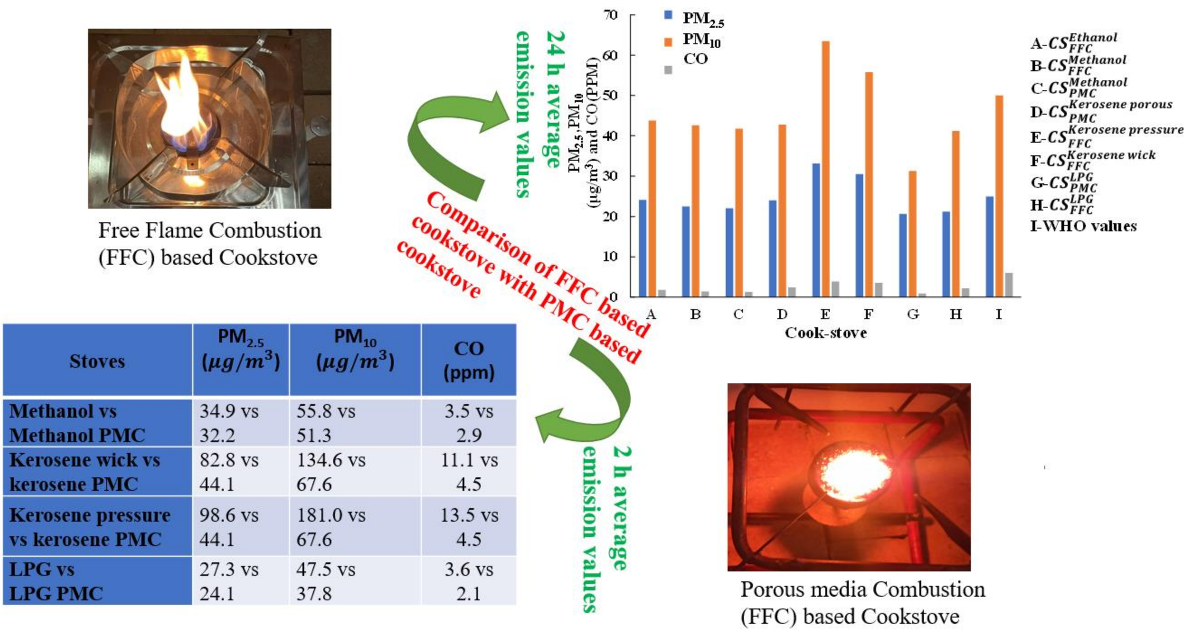
Abstract

The present study analyses the emission mitigation ability of a Porous Media Combustion (PMC) technology based cookstove (CS_{PMC}) compared to a Free Flame Combustion (FFC) technology based cookstove (CS_{FFC}). Emission of pollutants i.e., $PM_{2.5}$, PM_{10} and CO caused due to burning of fuels namely methanol, ethanol, kerosene and LPG in the kitchen environment are measured. The study incorporated exhaustive real-time indoor air quality (IAQ) measurements and presented the temporal variation of measured pollutant concentrations for 2 h (morning meal duration). In addition, 24 h average concentration of the measured pollutants is also compared with the limits prescribed in WHO guidelines for domestic settings. The results emphasised that the utilisation of CS_{PMC} would help in improving the IAQ of the kitchen area by decreasing the concentrations of $PM_{2.5}$, PM_{10} and CO. For 2 h duration measurements, the methanol cookstove based on PMC reduced the concentrations of $PM_{2.5}$, PM_{10} and CO by 7.7%, 8.1% and 17.2% respectively, compared to FFC cookstove. Similarly, in the case of PMC based LPG cookstove (CS_{PMC}^{LPG}) and kerosene cookstove ($CS_{PMC}^{Kerosene}$), the respective values were 11.7%, 20.4% and 41.6% and 55.3%, 62.6% and 66.6%. Among all the tested cookstoves, CS_{PMC}^{LPG} achieved the lowest emission values ($PM_{2.5}$: 20.6 $\mu g/m^3$; PM_{10}: 31.3 $\mu g/m^3$ and CO: 1 ppm) which are lower than the prescribed WHO values ($PM_{2.5}$: 25 $\mu g/m^3$; PM_{10}: 50 $\mu g/m^3$ and CO: 6 ppm).

Keywords: Indoor Air Quality; Domestic cookstoves; Porous Media Combustion; Free Flame Combustion; Particulate Matter.

Graphical Abstract



Stoves	$PM_{2.5}$ $(\mu g/m^3)$	PM_{10} $(\mu g/m^3)$	CO (ppm)
Methanol vs Methanol PMC	34.9 vs 32.2	55.8 vs 51.3	3.5 vs 2.9
Kerosene wick vs kerosene PMC	82.8 vs 44.1	134.6 vs 67.6	11.1 vs 4.5
Kerosene pressure vs kerosene PMC	98.6 vs 44.1	181.0 vs 67.6	13.5 vs 4.5
LPG vs LPG PMC	27.3 vs 24.1	47.5 vs 37.8	3.6 vs 2.1

Highlights

- The impact of PMC based cookstove on Indoor Air Quality is reported.
- Emissions of $PM_{2.5}$, PM_{10} and CO were measured for FFC and PMC based cookstoves.
- All PMC based cookstoves showed lower emissions than FFC based cookstoves.
- LPG based PMC cookstove showed 85.1% lower CO emission than WHO Limit.
- Cooking with PMC based cookstove would help in improving IAQ.

1. *Introduction*

The World Health Organization (WHO) estimates that household exposure to smoke from cookstoves causes indoor air pollution, which results in over 3.8 million deaths annually. (WHO 2014). Pollutants such as particulate matter, carbon monoxide, nitrogen oxides, volatile organic compounds, and polyaromatic hydrocarbon are released when biomass is burned in inefficient cookstoves. Exposure to these pollutants has been associated with a range of health effects, including lung cancer, Chronic Obstructive Pulmonary Disease (COPD), low birth weight, cataracts, pneumonia and tuberculosis (Pratiti et al. 2020; Rio et al. 2020; Sharma et al. 2019; De la Sota et al. 2018; Fullerton et al. 2008). Particulate Matter (PM) and Carbon Monoxide (CO) emissions are the principal components of indoor air pollution caused by domestic fuel burning (WHO 2014). PM and CO are generally emitted as a result of incomplete combustion of fuel in cookstoves. PM_{10} includes inhalable particles with diameters of 10 μm or less and $PM_{2.5}$ includes fine inhalable particles with diameters of 2.5 μm or less. Cardiovascular symptoms, such as cardiac arrhythmias and heart attacks, respiratory effects such as asthma and bronchitis are possible side effects of inhaling particulate matter (Du et al. 2016). Whereas, when CO is inhaled, it reacts with the haemoglobin in red blood cells to form carboxyhaemoglobin, which lowers the blood's ability to carry oxygen and raises the risk of both chronic and acute adverse health effects in adults, children, and foetuses. Acute exposures to CO can cause dizziness, muscle cramps and loss of consciousness and sometimes lead to death (Ernst et al. 1998).

To improve the indoor air quality of a household, nations across the world are adopting cleaner fuels such as LPG, CNG, methanol and ethanol. However, domestic cookstoves available for these fuels work on the principle of Free Flame Combustion (FFC) technology, which is inefficient and contribute to hazardous level of indoor air pollution. Various researchers compared the Indoor Air Quality (IAQ) level for biomass based cookstoves (Pratiti et al. 2020; Sharma et al. 2019). It is important to highlight that available research works are found to be disproportionate towards the measurement of pollutants concentration from biomass cookstoves and its effects on IAQ of the household. Very few studies were reported on the fuels like kerosene, ethanol, methanol and LPG and some of the important studies are discussed in the following section.

A lab study conducted by Kandpal et al. (1995) in the kitchen environment of dimensions 2.6×2.8×2.3 (m^3) showed that the use of LPG cookstove generates lower emission of CO than kerosene stoves. The field study conducted by World Bank to investigate the indoor air pollution in India showed that fuel type, kitchen type, and kitchen ventilation are the major parameters that need to be considered for emission measurements. Further, the findings of this study revealed that the households using cow dung had a five-fold higher risk of living-area emission concentrations than households using kerosene or LPG (Balakrishnan et al. 2004). Another field study was conducted to assess the IAQ for 55 households on the usage of fuels such as cow dung, wood, LPG, propane and kerosene. The results showed the presence of polyaromatic hydrocarbon emission from all the tested fuels (Gautam et al. 2013). A study conducted in Nigeria among the kerosene users showed that the emission of mean PM_{10} (246 $\mu g/m^3$) was ten folds higher than the WHO's guideline limit of PM_{10} (50 $\mu g/m^3$) (Adeniji et al. 2015). A lab study was conducted to compare the emissions of CO and $PM_{2.5}$ from kerosene cookstove, ethanol gel cookstove and methanol cookstove (Masekameni et al. 2015). The results revealed that the ethanol gel cookstove generates less $PM_{2.5}$ emission compared to the methanol and kerosene cookstove and all the emissions (CO and

$PM_{2.5}$) has been measured through the hood method (IS11760 1986) in which flue gases are separated from the surrounding air for measurement of exhaust emissions. Sidhu et al. (2017) compared the indoor and outdoor kitchen emissions from LPG cookstoves. The study depicted that the indoor kitchen showed the highest pollutants concentration (CO: 9.3 ppm; $PM_{2.5}$: 696.5 $\mu g/m^3$) followed by the outdoor kitchen (CO: 5.8 ppm; $PM_{2.5}$: 539.5 $\mu g/m^3$). The concentration of pollutants was found to vary depending on the style of the kitchen, the type of fuel used, and the location of the kitchen. Tagle et al. (2018) conducted a field study in Paraguay and measured the time-integrated samples (24 h) of $PM_{2.5}$ and continuous CO concentrations in kitchens that used wood, charcoal, LPG and electricity for cooking applications. The results showed that the kitchens using LPG resulted in the lowest CO and $PM_{2.5}$ concentrations. The field study conducted by Oluoch and Nyamasyo (2020) revealed that the kerosene produced 1.2 and 1.6 times higher $PM_{2.5}$ than charcoal and LPG cookstoves. To determine the exposure to $PM_{2.5}$ among pregnant women after LPG intervention, a pilot study was carried out in India, Rwanda, and Guatemala. The results showed that the LPG intervention reduced the kitchen $PM_{2.5}$ levels by 92% (Liao et al. 2021). The summary of the above-mentioned studies is presented in Table 1.

Table 1: Reported emission values from various cooking fuels

Fuel	**Usage duration (h)**	**Location**	**Kitchen volume (m^3)/area (m^2)**	**$PM_{2.5}$/PM_{10} ($\mu g/m^3$)**	**CO (ppm)**	**Study**	**Ref.**
LPG	1	India	16.7 (m^3)	-	1 (1 h average)	Lab	Kandpal et al. (1994)
Kerosene	1	India	16.7 (m^3)	-	3 (1 h average)	Lab	Kandpal et al. (1994)
LPG	-	India	-	73 (PM_{10})	-	Field	Balakrishnan et al. (2004)
Kerosene (wick)	-	India	-	203 (PM_{10})	-	Field	Balakrishnan et al. (2004)
LPG	-	India	-	342 (24 h average/$PM_{2.5}$)	-	Field	Gautam et al. (2013)
Kerosene	-	Nigeria	2.80 ×2.38 (m^2)	246.6±13.5 (24 h average/ PM_{10})	-	Field	Adeniji et al. (2015)
Ethanol	1	South Africa	-	99.5 (1 h average/$PM_{2.5}$)	7500 (1 h average)	Lab	Masekameni et al. (2015)
Methanol	1	South Africa	-	992.6 (1 h average/$PM_{2.5}$)	3200 (1 h average)	Lab	Masekameni et al. (2015)
Kerosene	1	South Africa	-	3180 (1 h average/$PM_{2.5}$)	9300 (1 h average)	Lab	Masekameni et al. (2015)
LPG	-	India	-	78.8 (24 h average /$PM_{2.5}$)	1.05 (24 h average)	Field	Sidhu et al. (2017)
LPG	3.4±1.3	Paraguay	40.1±13.8 (m^3)	52.3±18.9 (24 h	0.5±0.6 (24 h average)	Field	Tagle et al. (2018)

				average/ $PM_{2.5}$)			
LPG	-	Guatemala	31.6$\pm$10.2 (m^3)	27$\pm$13 (24 h average/ $PM_{2.5}$)	-	Field	Liao et al. (2021)

Encouraging the use of clean household cooking technologies are vital for developing countries to achieve sustainable development goal (SDG 7) by 2030 (The Energy Progress Report, 2021). Recently, the governments of various countries are promoting ethanol (Mudombi et al. 2018), methanol (Ozier et al. 2018) and LPG (Sharma et al. 2019) as a cleaner alternative to solid fuels to implement sustainability in cooking. Promoting the utilization of energy-efficient stoves can also help in cleaner cooking (Gautam et al. 2013). As of now, the stoves available in the commercial market for the combustion of these fuels (ethanol, methanol, kerosene and LPG) are based on Free Flame Combustion (FFC) principle. In case of FFC based devices, convection is the main mode of heat transfer which predominantly take place by gases. As gases are characterised by low thermal conductivity and radiative properties, the contributions of conduction and radiation heat transfer from combustion products to the load are negligible (Pantangi 2010). Consequently, the FFC based devices (including the cookstoves) are less efficient and they possess unfavourable characteristics such as lower thermal efficiency, high emission of pollutants, lower stable flame limits and power density (Avdic 2004). The concept of Porous Media Combustion (PMC) has been utilized to overcome the drawbacks of cookstove based on FFC principle. In PMC, the heat is transferred from a porous medium to the incoming fresh reactants is mainly by volumetric radiative heat transfer, resulting in excess enthalpy combustion (Vafai 2015). Therefore, PMC offer wider power modulation and flame stability range, higher thermal efficiency and lower emissions compared to their FFC based counterparts (Mujeebu et al. 2009). Studies on PMC based cookstoves were mostly focused on improving their efficiency by varying parameters like burner diameter, porosity (Muthukumar et al. 2011), porous material (Pantangi et al. 2007) and equivalence ratio (Deb and Muthukumar 2021). So far, no studies are reported on the indoor air quality due to use of PMC based cookstoves and its comparison with FFC based cookstoves.

It is evident from the literature, that there is no profound investigation on the levels of pollutants associated with methanol and ethanol conventional cookstoves and PMC based cookstoves in the actual kitchen environment. Therefore, the present work aims to investigate the level of pollutant emissions such as particulate matter ($PM_{2.5}$ and PM_{10}) and carbon monoxide (CO) for ethanol, methanol, kerosene and LPG fuelled cookstoves under indoor cooking conditions. Further, a comparative study on pollutant emissions of PMC and FMC based cookstove technologies using methanol, kerosene and LPG as fuel is also performed. Therefore, this study is first of its kind evaluating the impact of intervention of PMC based cookstoves in the kitchen environment.

2. *Materials and methods*

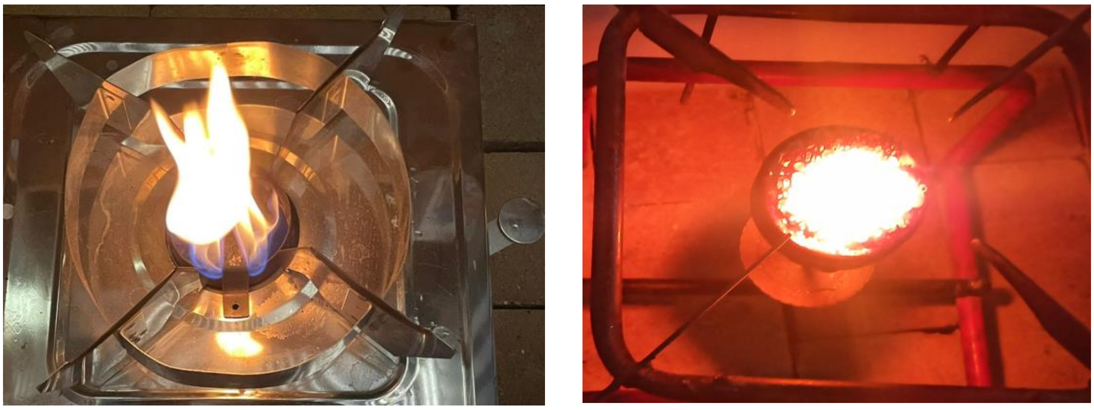
In this section, description and operating principle of FFC and PMC based cookstoves are presented. Further, the details of the kitchen model (representative of rural kitchen) and monitoring plan of pollutant emissions are also discussed.

2.1 FFC based cookstove (CS_{FFC})

The main mode of heat transfer from the FFC based cookstoves (CS_{FFC}) to the cooking vessel is convection, which is characterized by the flame that occurs in an open-air environment (Figure 1a). Gases have extremely low thermal conductivities and emissivities when compared to heat-conducting solids. As a result, the contributions of conductive and radiative heat transfer from the post-flame to the pre-flame zone in CS_{FFC} burner is negligible. Thus, these cookstoves are inefficient due to poor heat transport and they have unfavourable characteristics such as low thermal efficiency, low power density and high pollutant emissions.

2.2 PMC based cookstove (CS_{PMC})

The combustion in a PMC based cookstove (CS_{PMC}) takes place in a Porous Radiant Burner (PRB) which is made of highly emissive and conductive porous ceramic matrix. PRB uses a 3D porous ceramic matrix in the combustion zone to improve heat transfer from the burnt to the unburnt portion of the air-fuel mixture. Figure 1(b) shows a pictorial view of PMC based methanol cookstove developed at IIT Guwahati. The contributions of conductive and radiative heat transfer in the PRB are significant due to the large surface area, high thermal conductivity and good radiative characteristics. Convective heat transfer of CS_{PMC} is also better than CS_{FFC} due to the high heat transfer surface area of the porous matrix. Therefore, due to better conductive, radiative and convective heat transfer, the CS_{PMC} shows numerous benefits, such as higher thermal efficiency, higher power density, higher power modulation and lower emissions as compared to CS_{FFC}.



(a) (b)

Figure 1. Pictorial view of methanol cookstove (a) FFC and (b) PMC

2.3 Representative kitchen model

In the present study, the IAQ assessment has been carried out using the representative kitchen model developed at IIT Guwahati (Figure 2). The developed kitchen model is representative of the kitchen size of Indian households as per the study conducted by World Health Organization (WHO, 2014). The studies were conducted in a kitchen of dimensions 2.7×2.0×1.7 (m^3). The kitchen was provided with two windows of dimensions 0.13×0.23 (m^2) for ventilation. The reason for selecting such household construction is to get a comparative view of the result obtained from the field studies as mentioned in Table 1 which were mostly conducted in rural areas to monitor the emission values of pollutants. Another reason for the selection of such households is the government scheme of promoting clean cooking fuels i.e., ethanol and methanol in rural areas. Therefore, present household setup was developed to get the real time emission values from the cookstove.

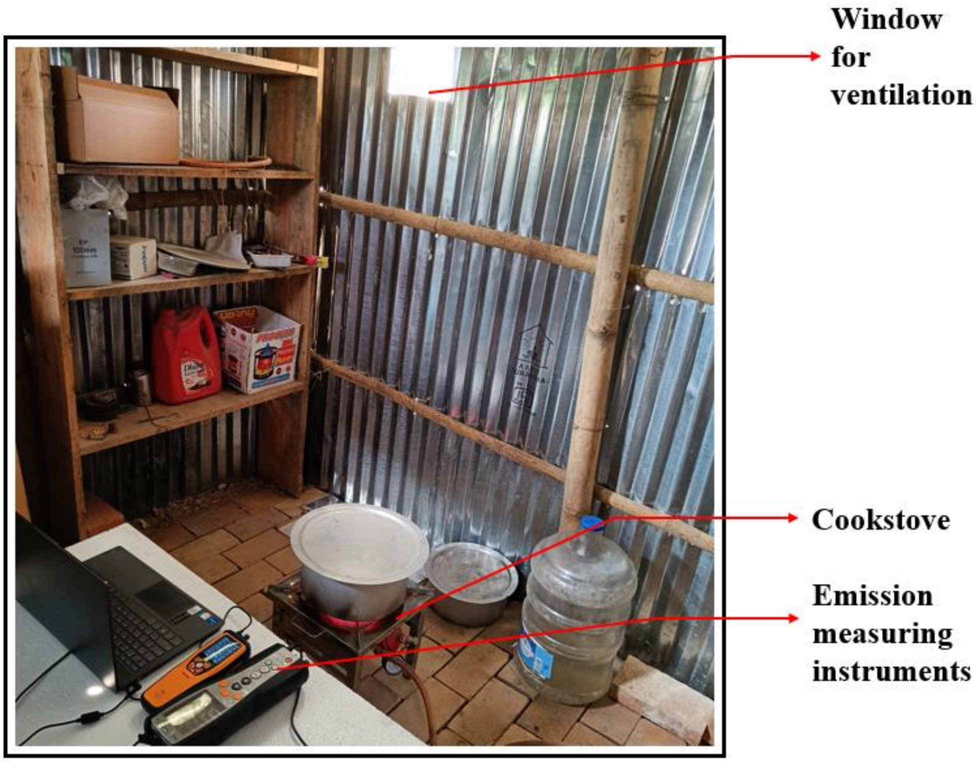


Figure 2. Representative kitchen model for the measurement of emission levels

In the developed kitchen model, IAQ was measured for eight different cookstoves namely FFC based cookstoves such as FFC methanol canister cookstove ($CS_{FFC}^{Methanol}$), FFC ethanol canister cookstove ($CS_{FFC}^{Ethanol}$), FFC kerosene pressure cookstove ($CS_{FFC}^{Kerosene\ pressure}$), FFC kerosene wick cookstove ($CS_{FFC}^{Kerosene\ wick}$) FFC LPG cookstove ($CS_{FFC}^{LPG}$) and PMC based cookstoves such as PMC methanol pressure cookstove ($CS_{PMC}^{Methanol}$), PMC kerosene pressure cookstove ($CS_{PMC}^{Kerosene}$) and PMC LPG cookstove (CS_{PMC}^{LPG}). $CS_{FFC}^{Methanol}$and $CS_{FFC}^{Ethanol}$ were provided by the Assam Petrochemical Limited and $CS_{FFC}^{Kerosene\ pressure}$, $CS_{FFC}^{Kerosene\ wick}$ and CS_{FFC}^{LPG} were bought from the commercial outlet. $CS_{PMC}^{Methanol}$, $CS_{PMC}^{Kerosene}$ and CS_{PMC}^{LPG} were developed at IIT Guwahati. The design specification of all the selected cookstoves and characteristics of the fuels used in the present work are presented in Table 2.

Table 2. Characteristics of fuels based on their cookstove

Type of cookstove	Cookstove	Burner	Power input (kW)	Thermal efficiency (%)	Fuel Tank capacity (l)	Ref.
FFC based cookstove	**Methanol**	Double canister	1.1-1.5	50-63	1.8 l	Maurya et al. (2022)
	Ethanol	Double canister	1.1-2.5	50-60	1.2 l	Present study

	Kerosene Pressure	Single roarer	1.5-3	51-56	2 l	Maurya et al. (2022)
	Kerosene wick	10 number of wicks	1-3	49-59	2 l	Maurya et al. (2022)
	LPG	Double burner	1-3	60-68	24.7 l	Muthukumar et al. (2011)
PMC based cookstove	**Methanol**	Silicon carbide with 90% porosity	1.8-3.5	60-67	3 l	Muthukumar and Maurya (2021)
	Kerosene Pressure	Silicon carbide with 90% porosity	1.5-3	55-64	3 l	Sinha (2017)
	LPG	Silicon carbide with 90% porosity	1-3	75-80	24.7 l	Muthukumar and Kaushik (2018)
Note: Lower Calorific Value (LCV) of kerosene (43.9 MJ/kg), ethanol (26.7 MJ/kg) and methanol (18.5 MJ/kg) were measured by bomb calorimeter at IIT Guwahati and for LPG (45.6 MJ/kg), LCV was measured using GC.						

During the experiments, the cookstoves were placed on the kitchen floor in the middle of the room. All the cookstove were charged by the fuel up to its 75% capacity and ignited in the kitchen itself.

2.4 Monitoring plan

Particulate matter (PM) and carbon monoxide (CO) were measured in the above-mentioned kitchen size for both cooking and non-cooking hours. The monitoring of air pollutants i.e., $PM_{2.5}$ and PM_{10} were conducted by air quality meter Temtop-M 2000. This instrument is sensitive to particles of aerodynamic diameter of 2.5 µm and 10 µm, which is the size range assumed to be the most important for affecting the health of people. All the pollutant concentrations were recorded at every minute in the memory of the instrument, which then downloaded into a personal computer. The CO level was measured by the instrument Testo 350 and the concentration was recorded every minute with the help of Testo easy emission software.

The Temtop-M 2000 air quality meter and CO monitoring device were placed next to each other on the wooden stand at a distance and height of 50 cm in the kitchen for 24 h. The height of 50 cm correlates to a person's breathing level in the kitchen in squatting position (Kandpal et al. 1994). For each stove, monitoring was done for 1 day (3 replicates on each stove) i.e., for each stove monitoring of pollutants was conducted for 3 consecutive days. The experiments were conducted for 18 days and reliability in stove operation was sustained throughout. The characteristics of the monitoring plan are listed in Table 3.

Table 3. IAQ monitoring plan

Factors	Description
Sampling Location	IIT Guwahati (50 cm away from the cookstove and a height 50 cm away from the floor)
Ventilation	Air exchange of 3.7/h
Sampling Duration	24 h
Cooking hours	(8 A.M to 10 A.M)
Cookstove technology	FFC and PMC
Pollutant monitored	PM (PM_{10}, $PM_{2.5}$) and CO
Sampling time interval	1-min data logging

2.5 Statistical analysis

The mean comparison test was done to determine the significant difference in the emission of gaseous pollutants i.e., $PM_{2.5}$, PM_{10} and CO from the CS_{FFC} and their respective CS_{PMC}. A two-tailed student t-test at the 95% confidence level (p<0.05) is used as the determinant for evaluation of statistical difference in emission values. The t-value is defined as the ratio of variance between samples groups and variance within the groups and calculated by using Eqn. 1.

$$t = \frac{\overline{x_1} - \overline{x_2}}{\sqrt{\frac{{S_1}^2}{n_1} + \frac{{S_2}^2}{n_2}}} \tag{1}$$

where, x-represent the mean values of concentration of pollutants, n- represent the number of observations (120) and S is the variance of the pollutant concentration values. Subscript 1 and 2 denotes the CS_{FFC} and CS_{PMC} values, respectively.

The larger and smaller t values denote that the groups are different and similar, respectively. P-values are lies between 0-1and it is evaluated with the help of t distribution Table. A lower p-value (p<0.05) represents that the obtained result is statistically significant and a higher p-value (p>0.05) represents that the obtained result is not statistically significant. The t-value is evaluated using the MS Excel (Excel-2019, Version 2203) statistical tool and the corresponding p-value is evaluated with the help of t distribution table.

3. Results and discussion

Monitored emission values of pollutants emitted from conventional CS_{FFC} i.e., canister based methanol and ethanol cookstoves, kerosene pressure and wick cookstoves and LPG cookstove are reported in this section with timeline plots and pairwise statistical comparison with CS_{PMC}. Further, an overall comparison has been made with the WHO guidelines for 24 h average concentration of emission values of all the mentioned cookstoves.

3.1 Monitoring results

The emission of pollutants from all the tested cookstoves are measured for 2 h and 24 h duration and discussed in subsequent sections. During the experiments, all the stove were operated at a firepower of 2 kW except $CS_{FFC}^{Methanol}$. In case of $CS_{FFC}^{Methanol}$, the maximum firepower is limited to 1.5 kW due to cookstove design (Maurya et al. 2022).

3.1.1 Temporal variation in $PM_{2.5}$ and PM_{10} concentrations for CS_{FFC}

The monitored values of $PM_{2.5}$ and PM_{10} for the cookstove operating on FFC are shown in Figures 3 and 4. The $PM_{2.5}$ and PM_{10} concentrations in the kitchen area before starting the experiment were found in the range of 20-23 $\mu g/m^3$ and 38-42 $\mu g/m^3$, respectively. The observation shows that during the ignition phase (first 5 min of combustion), the $PM_{2.5}$ and PM_{10} concentrations were reached the peak values of about 210 $\mu g/m^3$ (Figure 3) and 455 $\mu g/m^3$ (Figure 4) for kerosene pressure and 132 $\mu g/m^3$ (Figure 3) and 200 $\mu g/m^3$ (Figure 4) for wick cookstoves, respectively and then, it decreased with time. The sudden peak in the $PM_{2.5}$ and PM_{10} concentration values during the initial phase of operation showed the unstable combustion of fuel in the conventional kerosene pressure and wick cookstoves. After 10 min of operation, these cookstoves showed a decreasing trend in the emission of $PM_{2.5}$ and PM_{10} concentrations and after 30 min of operation, a less variation in the range of emission value was observed. However, methanol, ethanol and LPG cookstoves reported concentration value in the range of 33-39, 35-42 and 25-30 $\mu g/m^3$ for $PM_{2.5}$ and 50-60, 50-65 and 40-50 $\mu g/m^3$ for PM_{10}, respectively throughout their burn cycle of 2 h. This showed there is less variation in the concentration of $PM_{2.5}$ and PM_{10} during the burn cycle of cookstove which represents a stable combustion of fuel in their respective cookstoves. The measured concentrations of $PM_{2.5}$ and PM_{10} for conventional methanol, ethanol and kerosene wick cookstove were compared with the reported literature values. It was observed that a similar trend of $PM_{2.5}$ variation was reported in the lab study conducted by Masekameni et al. (2015) for kerosene wick cookstove (average concentration – 3180 $\mu g/m^3$ for 1 h duration). However, in case of methanol and ethanol cookstoves reported by Masekameni et al. (2015), all $PM_{2.5}$ emission has been found very high up to 5000 $\mu g/m^3$ for first five min and then showed a constant lower concentration of around 100 $\mu g/m^3$ for the burn cycle of 1 h. The higher concentration observed in their study is mainly due to use of hood method (IS11760 1986) for measurement of emissions. In present study, the average $PM_{2.5}$ concentration of conventional methanol and ethanol cookstoves was 35 and 37 $\mu g/m^3$, respectively during the burn cycle of 2 h.

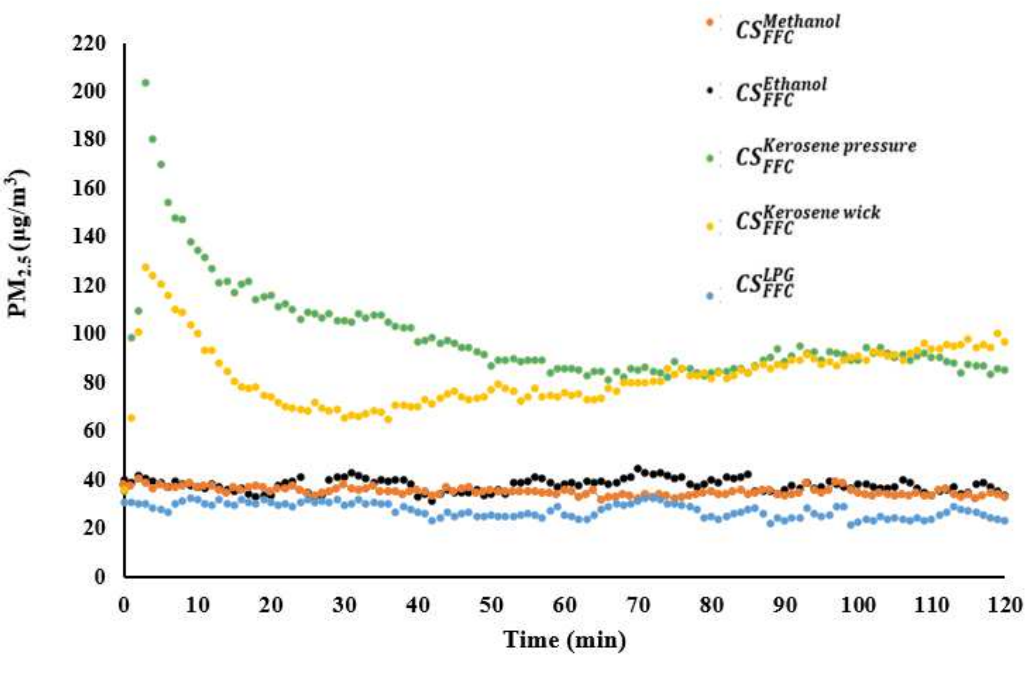


Figure 3. $PM_{2.5}$ concentration variation for the 2 h burn cycle of CS_{FFC}

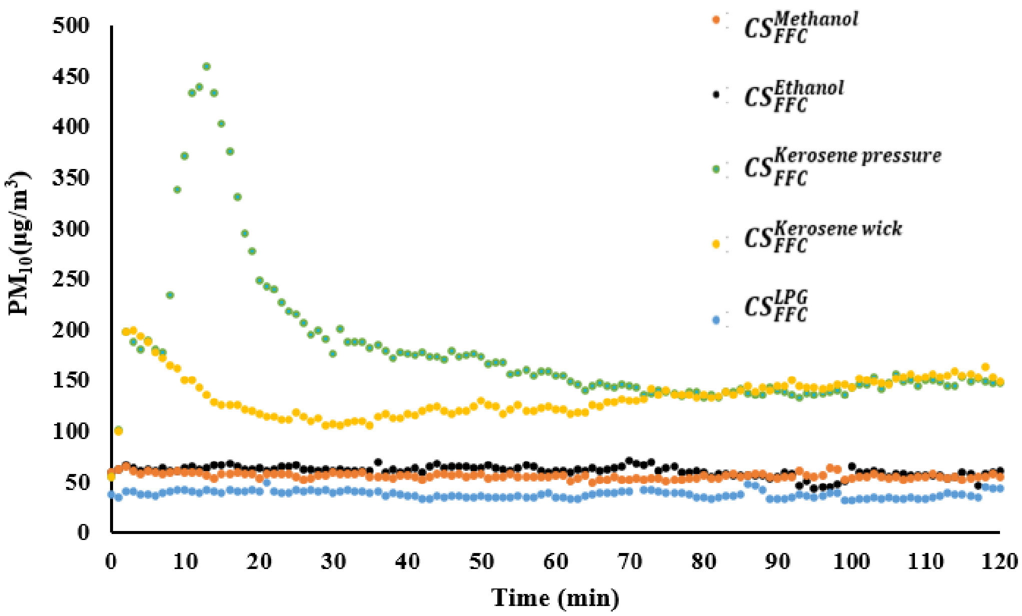


Figure 4. PM_{10} concentration variation for the 2 h burn cycle of CS_{FFC}

3.1.2 Temporal variation in CO concentrations for CS_{FFC}

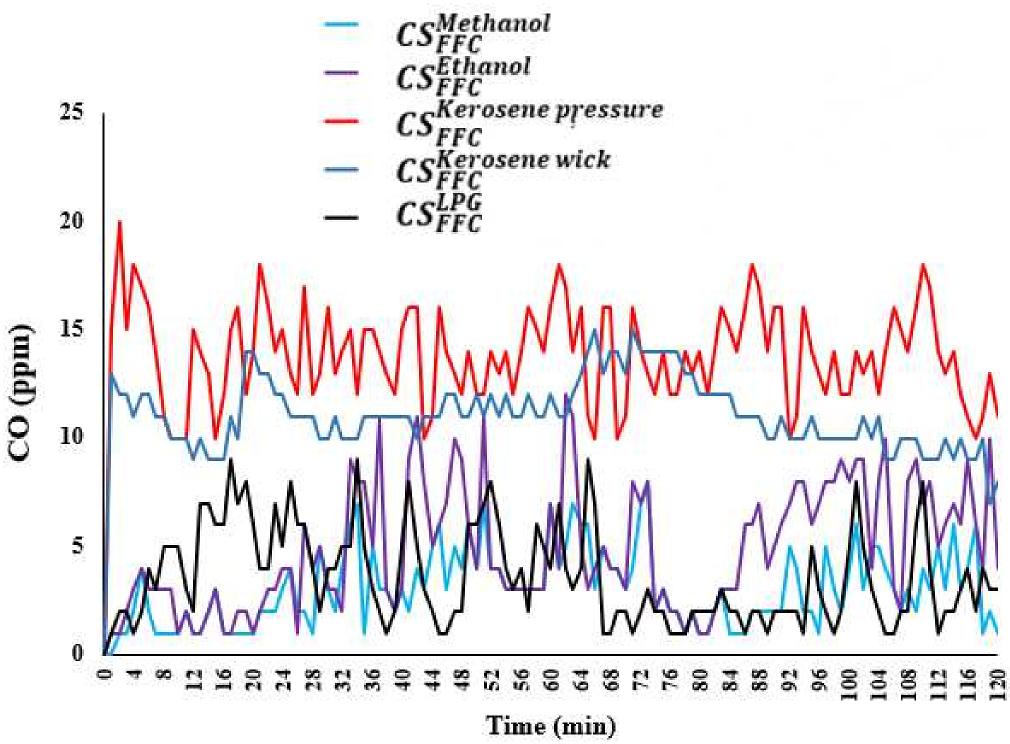


Figure 5. CO concentration variation for the 2 h burn cycle of CS_{FFC}

CO emission was also recorded simultaneously along with PM observations. The measured CO concentration in the kitchen area before starting the experiment lies in the range of 0-1 ppm. As shown in Figure 5, the peak CO concentration reported during 2 h of burn cycle from kerosene pressure and wick cookstoves was 18 and 16 ppm, respectively. The mean 2 h CO concentration was varied in the following order, kerosene pressure stove (13.6 ppm), kerosene wick stove (11.1 ppm), ethanol canister stove (4.8 ppm), LPG stove (3.6 ppm) and methanol canister stove (3.1 ppm). It was observed that the methanol canister cookstove showed the lowest CO concentration among all the tested cookstoves. This is mainly due to lowest firepower and cleaner combustion ability of methanol (Maurya et al. 2022). CO emission of present study showed a similar observation made by Masekameni et al. (2015) for kerosene wick, ethanol and methanol cookstoves. However, the average CO concentration for kerosene wick, ethanol and methanol cookstoves were 9300 ppm, 7500 ppm and 3200 ppm, respectively which is considerably higher than the present study. This is mainly due to use of hood method for the measurement of CO emission.

3.2 Comparison of emission values of FFC cookstoves with PMC based cookstoves

In this section a comparison between the emission values of CS_{FFC} and CS_{PMC} are presented. The pairs of cookstoves considered for the comparison are- $CS_{FFC}^{Methanol}$ vs $CS_{PMC}^{Methanol}$, $CS_{FFC}^{Kerosene\ pressure}$ vs $CS_{PMC}^{Kerosene}$, $CS_{FFC}^{Kerosene\ wick}$ vs $CS_{PMC}^{Kerosene}$ and CS_{FFC}^{LPG} vs CS_{PMC}^{LPG}.

3.2.1 Comparison of $PM_{2.5}$ and PM_{10} emissions of CS_{FFC} **and** CS_{PMC}

Pairwise comparison of particulate matter i.e., $PM_{2.5}$ and PM_{10} emissions between the CS_{FFC} and CS_{PMC} are shown in Tables 4 and 5. The mean values (for 2 h burn cycle) of $PM_{2.5}$ and PM_{10} were found to be the lowest for CS_{PMC}^{LPG} and highest for $CS_{FFC}^{Kerosene\ pressure}$. It was found that the t-value for all pairs of cookstoves was greater than 1. And the p-value corresponding to the evaluated t-value was less than 0.05 as shown in Tables 4 and 5, which represents that there was a statistically significant difference between the measured emissions of all the cookstoves. Among all the paired sets of cookstove, $CS_{PMC}^{Methanol}$ and $CS_{FFC}^{Methanol}$ showed the lowest t-values among all the compared cookstoves (Table 4 and 5), which reflects that there is less difference between the groups (as mentioned in **section 2.5**). Although the percentage difference in emission values is significant between $CS_{PMC}^{Methanol}$ and $CS_{FFC}^{Methanol}$ (i.e., 7.7% for $PM_{2.5}$ and 8.1% for PM_{10}) but less in comparison to other pair of FFC and PMC based cookstoves. As all the cookstove were operated at similar input power (2 kW) for comparison except $CS_{FFC}^{Methanol}$, which was operated at lower input power (1.5 kW) resulting in comparable emission values of $PM_{2.5}$ and PM_{10} to $CS_{PMC}^{Methanol}$. It was also observed that the $CS_{PMC}^{Kerosene}$ showed the highest 55.3% (Table 4) and 62.6% (Table 5) reduction in $PM_{2.5}$ and PM_{10}, respectively compared to the conventional kerosene pressure cookstove. The highest percentage reduction in particulate emission is possible only due to efficient combustion in porous media as reported in various literatures (Guerrero et al. 2021; Ciria et al. 2022). The Guerrero et al. (2021) reported the reduction of 61% in particulate matter emission due to use of porous silicon carbide ceramics in residential wood combustion system. Another study conducted by Ciria et al. (2022) for biomass combustion was also showed a reduction of more than 60% by placing the ceramic foam just above the combustion region. This reduction is mainly due to the homogeneous combustion inside the porous matrix (Mujeebu et al. 2009). Thus, the obtained result in the present study is in the agreement with the statement of reduction of particulate matter emission with the use of PMC based technology.

Table 4. Pairwise comparison of $PM_{2.5}$ emissions of CS_{PMC} with CS_{FFC}

Cookstoves	$PM_{2.5}$ ($\mu g/m^3$)	Statistical analysis		
		t-test	p-value	% decrease
Methanol vs Methanol PMC	34.9 vs 32.2	4.2	0.01	7.7
Kerosene pressure vs kerosene PMC	98.6 vs 44.1	27.8	0.00	55.3
Kerosene wick vs kerosene PMC	82.8 vs 44.1	25.3	0.00	46.7
LPG vs LPG PMC	27.3 vs 24.1	3.38	0.00	11.7

Table 5. Pairwise comparison of PM_{10} emission of CS_{PMC} with CS_{FFC}

Cookstoves	PM_{10} ($\mu g/m^3$)	Statistical analysis		
		t-test	p-value	% decrease
Methanol vs Methanol PMC	55.8 vs 51.3	2.54	0.01	8.1
Kerosene pressure vs kerosene PMC	181.0 vs 67.6	16.8	0.00	62.6
Kerosene wick vs kerosene PMC	134.6 vs 67.6	25.8	0.00	49.7
LPG vs LPG PMC	47.5 vs 37.8	12.9	0.00	20.4

3.2.2 Comparison of CO emissions of CS_{FFC} **and** CS_{PMC}

Table 6 presents the pairwise comparison of mean CO emission for 2 h for CS_{PMC} and CS_{FFC}. All the CS_{PMC} showed statistically significant differences in the emissions as compared to the CS_{FFC}. The t-value is greater than 1 and p value is less than 0.05 for all the compared sets of cookstove. Among all the tested cookstoves, $CS_{FFC}^{Kerosene\ pressure}$ reported the highest decrease of 66.6%, followed by $CS_{FFC}^{Kerosene\ wick}$ 59.4% and CS_{FFC}^{LPG} 41.6%, respectively in CO emission as compared to their PMC based counterparts. The percentage reduction in CO emission due to use of CS_{PMC} is mainly due to higher surface area of porous matrix, which leads to the longer residence time and results in lower CO emission (Guerrero et al. 2021). Several studies highlighted the reduction in CO emission with the use of PMC based technology (Muthukumar and shyamkumar 2013; Kaushik and Muthukumar 2020; Deb et al. 2021). Muthukumar and shyamkumar (2013) reported the maximum reduction in CO emission from 250 ppm to 10 ppm and Deb et al. (2021) reported the reduction in CO emission from 190 ppm to 42 ppm in the LPG operated PMC based cookstoves. Similarly, Kaushik and Muthukumar (2020) reported the reduction in CO emission from 682 ppm to 268 ppm due to use of PMC based kerosene pressure stove. However, the emissions reported in the above-mentioned studies are associated with the measurement by hood method (IS11760 1986), which measures the emission directly from a small opening of hood through a flue gas analyser. However, in the present study, the values of CO emissions was measured in the kitchen environment.

Table 6. Pairwise comparison of CO emission of CS_{PMC} with CS_{FFC}

Cookstoves	CO (ppm)	Statistical analysis		
		t-value	p-value	% decrease
Methanol vs Methanol PMC	3.5 vs 2.9	4.4	0.00	17.2
Kerosene pressure vs kerosene PMC	13.5 vs 4.5	33.1	0.00	66.6
Kerosene wick vs kerosene PMC	11.1 vs 4.5	22.2	0.00	59.4
LPG vs LPG PMC	3.6 vs 2.1	5.8	0.00	41.6

3.3 Emission values comparison with WHO Guidelines

The 24 h average concentration of $PM_{2.5}$, PM_{10} and CO from all the CS_{FFC} and CS_{PMC} are shown in Figure 6. The results obtained during the monitored periods are compared with the WHO guidelines. It was found that the highest concentrations of $PM_{2.5}$, PM_{10} and CO were detected during the operation of $CS_{FFC}^{Kerosene\ pressure}$, highlighting the adverse impact of conventional kerosene cookstove on indoor air quality. The emission value of $PM_{2.5}$ and PM_{10} for kerosene pressure stove were higher by 32.4% and 27%, respectively than the limit value suggested by the WHO. Among all the tested cookstoves, CS_{PMC}^{LPG} showed the lower emission of the studied pollutants and their values were 17.6%, 37.4% and 85.1% lower than the prescribed WHO values for $PM_{2.5}$, PM_{10} and CO i.e., 25 and 50 $\mu g/m^3$ and 6 ppm, respectively. All the cookstoves were found to be emitting lower CO emission value compared to WHO guidelines.

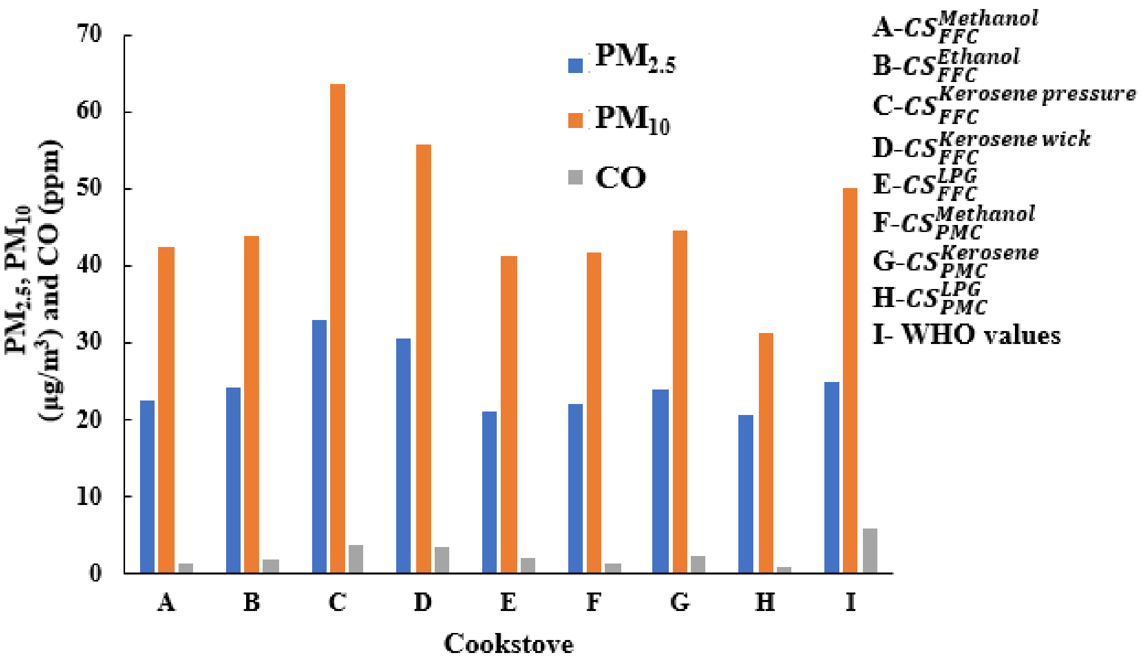


Figure 6. Average concentration of $PM_{2.5}$, PM_{10} and CO on 24 h basis

3.4 Comparison of IAQ emission values with literature for CS_{FFC}^{LPG} and $CS_{FFC}^{Kerosene\ wick}$

The emission values of CO and PM obtained from the conventional LPG and kerosene cookstove's from kitchen environment that are reported in literature (Table 1) for 24 h and 1 h duration was compared with the present study. Table 7 shows the comparison of $PM_{2.5}$, PM_{10} and CO emissions values with literature values.

Table 7. Comparison of $PM_{2.5}$, PM_{10} and CO average emission concentration with literature values

Cookstoves	CO (ppm)	PM_{10} ($\mu g/m^3$)	$PM_{2.5}$ ($\mu g/m^3$)	Monitoring time	Reference
LPG	3.6	47.5	27.3	2 h	Present study
kerosene	11.1	134.6	82.8	2 h	Present study
LPG	1.2	41.2	21.2	24 h	Present study
kerosene	3.5	55.8	30.5	24 h	Present study
LPG	3	-	-	1 h	Kandpal et al. 1995
Kerosene	6	-	-	1 h	Kandpal et al. 1995
LPG		1054	342	24 h	Gautam et al. 2013
LPG	1.05	-	78.8	24 h	Sidhu et al. 2017
LPG	0.5 ± 0.6	-	52.3 ± 18.9	24 h	Tagle et al. 2018
LPG		-	27 ± 13	24 h	Liao et al. 2021

The comparison was done to know the difference in emission values reported in available literature and emission values obtained from the IAQ assessment of model kitchen environment developed in the present study. It was observed that for 24 h and 2 h monitoring period of CO emission values were similar to the studies reported in literature. Whereas the emission of PM available in some literature was much higher than the values observed from the present study. The reason for such higher emission value is the adaptation of different cooking methods and fuels in their study which increases the PM emission (Gautam et al. 2013; Sidhu et al. 2017). In the present study, the emission values of PM were taken from the developed kitchen environment in which only one cookstove was used at a time for the particular duration and whose emission value was not influenced by the other residential emissions.

There is no study reported on the emission values of CO and PM in the actual kitchen equipped with porous media combustion based LPG, kerosene and methanol cookstoves and for conventional methanol and ethanol based cookstoves and therefore, these values were not compared with the literature.

4. Conclusions

A study was conducted which includes the monitoring of pollutants in a developed kitchen room which represents the rural environment with four different fuels i.e., ethanol, methanol, kerosene and LPG. This is the first of its kind study, which comprehensively monitored the emission values of $PM_{2.5}$, PM_{10} and CO from CS_{PMC} and compared it with the conventional CS_{FFC}. The 2 h real time concentration monitoring during cooking hours established that CS_{PMC} shows a significant reduction ($p < 0.05$) in pollutants emission. The maximum reduction of 55.3%, 62.6% and 66.6% were found due to the usage of $CS_{PMC}^{Kerosene}$ for PM_{10}, $PM_{2.5}$ and CO, respectively as compared to $CS_{FFC}^{Kerosene\ pressure}$.Further, the 24 h average concentration of the studied pollutants and its comparison with WHO guidelines is also a major contribution of the study. Results showed that all the developed CS_{PMC} in the combustion lab of IIT Guwahati, showed a significantly lower value of pollutants. The study also further reveals that kerosene pressure and wick cookstove are emitting higher emissions than WHO guidelines for $PM_{2.5}$ and PM_{10} by 32.4% and 27%; and 22% and 11.6%, respectively. The $CS_{PMC}^{Kerosene}$ showed a reduction of 4% and 10.8% for $PM_{2.5}$ and PM_{10}, respectively than WHO guidelines. The maximum reduction due to use of CS_{PMC} was found in case of CS_{PMC}^{LPG} and there was a reduction by 17.6%, 37.4% and 85.1% for the $PM_{2.5}$, PM_{10} and CO, respectively, then the prescribed WHO values. Hence, the present study established that the emissions of pollutants from household cooking fuels in CS_{FFC} have higher emission compared to CS_{PMC}. Therefore, cookstoves based on PMC can be the plausible solution to achieve better IAQ and health benefits.

Author's Contribution

Pratibha Maurya- Methodology, Investigation, Data Curation, Writing – Original Draft

Muthukumar Palanisamy- Conceptualization, Supervision, Writing- Reviewing and Editing

Anandalakshmi Ramalingam- Reviewing and Editing

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