

Research Article

Carbon Emission Reduction Potentials of Improved Biomass Cookstoves Used in Gambella Refugee Camps, Southwest Ethiopia

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Abstract

In many countries of the world, households burn firewood or biomass to fulfill their cooking and heating needs. The excessive reliance on biomass fuels by inefficient traditional cookstove produces and emits substantial amount of smoke which brings effects associated with high indoor air pollution, deforestation, climate change and losses productivity. Therefore, this study focused on carbon emission reduction potentials of improved biomass cookstoves used in Gambella refugee camps and compares it with traditional open-fire stove. For this study, Water Boiling Test (WBT) was carried out at laboratory level. The most commonly used improved biomass cookstoves and the three stone traditional cook stove were selected for the assessment and comparison. The emission of greenhouse gasses (carbon monoxide, carbon dioxide and particulate matters) was used as indicators to compare the emissions of each stove. The results indicated that, three-stone open-fire traditional stove, Clay (User Centered Design-UCD), Flexy and Tikikil stoves were found to be the preferred mode of biomass cooking stove used by most refugees. From the experimental test results, the performance model showed a significant reduction in greenhouse gasses and/or pollutant (CO₂, CO, and PM_{2.5}) concentrations. The use of one Flexy stove could avoid the emission of 1.21 tons, Clay 1.15 tons, and Tikikil 0.96 tons of CO₂e per stove per year. The average amount of CO emission from the three-stone stove was 1105ppm and from ICS was 370.3 ppm. Particulate matter (PM_{2.5}) emissions of Flexy, Clay, Tikikil and Traditional cookstoves were recorded as 329, 339, 337, 614 mg respectively. Therefore, it can be conclude that improved biomass cook stoves can produce less smoke and reduce greenhouse gas emissions and health effects. Thus, concerned organizations should disseminate and monitor improved biomass cooking stoves for the refugees so as to protect individuals from negative impact of traditional three-stone cookstoves.

Keywords

Emission Reduction, Gambella, Improved Biomass Cookstoves, Refugee, Water Boiling Test

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1. Introduction

Globally, more than one-third (over 2.8 billion) of peoples lack access to modern energy and relies on combustion of traditional solid biomass through inefficient cookstoves to fulfill their primary energy needs [4, 42, 46, 56]. Cutting of trees and traditional fuelwood consumption for cooking purposes result in adverse effects on the environment. This in turn traps heat and warms the Earth, leading to climate change and its associated devastating consequences [54]. Worldwide, approximately around 1–2.4 Gt CO₂e of greenhouse gasses (GHGs) are emitted annually due to the production and use of fuelwood and charcoal by inefficient cookstoves, which are 2–7% of the global anthropogenic emissions [4, 12]. In addition, burning biomass fuels in traditional cookstoves or open fires emit large quantities of fine particulate matter (PM_{2.5}) and carbon monoxide (CO) [5]. Cooking with solid-fuels contributes to 12% of the global ambient PM_{2.5} burden [11] and to 25% of ambient black carbon [10]. This brings significant health disorders such as respiratory [6], blood pressure, and cardiovascular disorders mostly among women [27, 58], as well as 3.2 million premature deaths per annum as of 2020 [55, 56]. Without any major change in policy, the number of people relying on traditional biomass fuels in 2030 is expected to remain roughly the same as now, about 40% of the current world population [23]. Better strategies like improved cook stoves (ICSs) to reduce carbon emissions have the potential of simultaneously mitigating climate change, conserving forests and improving human livelihoods [14].

Over 80% of the populations in Africa rely on solid biomass or firewood in meeting their cooking energy needs and from this only 11% of the population makes use of clean cookstoves and fuels. This has undoubtedly contributed to deforestation and the current climate change crisis [9]. In the 1990s, largely from developing countries, forests released about 5.8 Gt per year, which was more than all forms of transport combined [44, 52]. Recent estimates show that over 890 million people in sub-Saharan Africa depend on traditional fuels as their primary energy sources [24]. The incomplete combustion of biomass fuels in traditional cookstoves also has an adverse effect on human health and climate due to the formation of black carbon [54]. Indoor air pollution from traditional biomass fuels has a disproportionate impact on women and is listed among the top three causes of death in most countries of Sub-Saharan Africa [29]. IEA [61] estimates that Sub-Saharan Africa depends on biomass for upwards of three-quarters of its energy, and that without major policy changes the vast majority of people will continue to rely on biomass fuels for the foreseeable future. Efficient biomass-based combustion devices and densified solid biofuel technology for energy production is promising to reduced greenhouse gas (GHG) emissions [60]. The fuel in improved cookstoves is burned more efficiently, releasing reduced amounts of CO₂ into the atmosphere. Energy-efficient cookstoves therefore offer many health, community and environmental benefits [13].

Ethiopia, like many African countries, is heavily reliant on biomass-based energy sources. The largest energy supply comes from waste and biomass covering the highest share of the total primary energy [39]. This excessive reliance on biomass fuels and traditional open-fire cookstoves produces and emits substantial amount of smoke which affects human health associated with high indoor air pollution, high deforestation, climate change and losses of production opportunity [40, 49]. In Ethiopia, ~72,400 peoples die every year due to indoor air pollution from biomass fuel and kerosene [36]. The government of Ethiopia (GoE) is striving to enhance energy access across the country by 2030, with an increasing rate of access by 1.7% annually from 2010–2019 to reduce CO₂ emissions [2]. There is a continued wide-spread of fuel saving improved cookstove technologies to reduce pressure on forests and the adverse impact of indoor air pollution for the last decades. Now a day, 1.2 million people of low-income households in Ethiopia have sustainable access to improved cooking technologies that use less biomass fuel [16]. Thus, the promotion of such clean cookstoves is an important measure to improve the health and environmental conditions of people who are still relying on solid fuel burning for daily domestic energy supply [34, 60].

The Moving Energy Initiative (MEI) estimates that forcibly displaced families living in camps are burning 64,700 acres of forest (equivalent to 49,000 football pitches) each year contributes to unsustainable wood harvesting, causing deforestation and reducing carbon uptake by forests [28]. To address traditional use of fuels, significant and devoted efforts have been made on the advancement of cook-stoves over the last-to-recent decades [34]. Currently, several prior strategies has been designed to reduce fuel-wood consumption and GHG emission which includes implementing ICSs, increasing fuel efficiency and changing the cooking behaviors [19, 32]. The main reason for distributing ICSs is to reduce forest degradation [14, 32, 47], reduce the GHGs emission [14, 37], reduce indoor and outdoor pollution [45, 59], improve the quality of health [15] and enhance the socioeconomic benefit [41]. ICSs can significantly reduce household exposure to indoor-air pollution resulting from burning of biomass fuels and abate emissions of CO₂ by up to 75% compared to traditional stoves. Efficient stoves can save carbon, reduce women's workload and improve air quality [48]. Replacing traditional stoves with fuel-efficient and lower-emitting improved stoves can helps to mitigate those socio-economic and environmental problems [3, 7, 14]. This study, therefore, evaluated the potential of improved biomass cooking stoves in greenhouse gas emission reduction at laboratory level more holistically by considering CO₂, CO and PM_{2.5} and compares it with three-stone open-fire traditional cookstoves.

2. Materials and Methods

2.1. Materials

The following instruments were used for testing emissions of each identified biomass cookstoves.

- 1) Exhaust hood, including blower and collection duct with a variable ranges from 80-150 m³/h
- 2) CO₂/CO analyzer with a variable ranges from 0–10,000/0–500 ppm
- 3) Bomb calorimeter
- 4) Flow grid
- 5) Scattering measurement with a variable ranges from 0-5000 µg/m³
- 6) Carbon monoxide with a variable ranges from 0-2000 ppm
- 7) Carbon dioxide with a variable ranges from 0-5000 ppm

2.3. Description of Biomass Cookstoves



Source: Own survey data, 2022

Figure 1. Types of biomass cooking stoves used by the refugees.

Among the various available biomass cookstoves in each refugee camps; Flexy, Clay (UCD–User Center Design), Tikikil and Traditional open-fire cook stoves (TCS) was used for the study since they are the most common stoves adopted by a large proportion of the refugees (Figure 1).

2.4. Water Boiling Test (WBT)

The water boiling test (WBT version 4.2.3) was conducted in the Addis Ababa laboratory of the Ethiopian Ministry of Water Irrigation and Energy to determine emissions of GHGs by each identified stoves. The emissions of CO and CO₂ by each biomass stove's were measured using IAQ-CALC meter

8) Filter-based particulate matter setup

2.2. Study Site Description and Sampling Technique

The study was carried out in selected refugee camps of Gambella region which is situated 766 km to the Southwest of Addis Ababa (capital of Ethiopia). Gambella is located at 7 ° 55' 19.087" N latitude and 34 ° 9' 11.501" E longitudes with an altitude of about 300-2300 m above sea level. For this study, three refugee camps i.e., Ngnyiel, Phignido and Jewi were selected purposively for the assessment due to the entirely dependence on biomass fuelwood for cooking and distribution of improved biomass cookstoves (IBCSs). The experimental test was carried out in Addis Ababa laboratory of the Ethiopian Ministry of Water, Irrigation and Energy (MoWIE) Center to evaluate performance of the stoves.

while fine particulate matter (PM_{2.5}) data were collected using an indoor air pollution meter. Both the IAQ-CALC meter and IAP Meter stored the data on data logger minute-by-minute over the entire measurement period. The test was done three times for each stove type and data on CO₂, CO and PM_{2.5} emissions were collected three times following the standard WBT version 4.2.3 in a controlled laboratory setting [20]. Background emissions were also accounted for by measuring concentrations of CO₂, CO and PM_{2.5} before and during the test. The air temperature was 17.5–19 °C and the local boiling point was 94 °C. For this study, locally available and common type of biomass fuelwood (i.e., meth) was used to test the emission of each identified cookstoves. The wood sample was

dried properly using sunlight and the average moisture content of the sample fuelwood was 8.32%.

2.5. Estimation GHG Emission Reduction

2.5.1. Estimation of the Carbon Dioxide (CO₂) Emission Reduction

Estimate of the carbon dioxide (CO₂) reduction is calculated using the AMS-II G methodology [50]. Emission reduction from the use of efficient cooking stoves will be calculated as a product of the amount of woody biomass saved, *i.e.* fuel consumption, the fraction that is considered non-renewable biomass (f_{NRB}), the emission factor for fossil fuel and the net calorific value (NCV) of biomass [30].

$$ER_y = B_y \times f_{NRB,y} \times NCV_{Biomass} \times EF \quad (1)$$

Where:

ER_y = Emission reduction during year y in tCO₂e

B_y = Quantity of fuelwood saved (substitute or displaced) in tone

$f_{NRB,y}$ = Fraction of non-renewable woody biomass saved by the project activity in year y (UNFCCC, [50] default value for Ethiopia is 88%)

$NCV_{Biomass}$ = Net calorific value of the non-renewable woody biomass that is substituted (IPCC Change default for wood fuel is 0.015 TJ/ton or 15 MJ/kg)

EF = default emission factor (per unit of energy) which is 81.6 tCO₂/TJ or 112 g CO₂/MJ

$$B_y = B_{old,cooking\ stove} \times \left(1 - \frac{\eta_{old}}{\eta_{new\ ICS}}\right) \quad (2)$$

Where,

$\eta_{new\ ICS}$ = the efficiency of ICS in the study
 $\eta_{old} = 10\%$ [The default value of 10% will be applied as the systems to be replaced are three stone fires]

$$B_{old,cooking\ stove} = B_{y,device} \times L_y \quad (3)$$

Where,

L_y = The default net to gross adjustment factor of 0.95 was applied to account for leakages

$B_{y,device}$ = Average annual consumption of woody biomass per appliance in tones per year

$$B_{y,device} = B_{old,caption} \times N_{resident\ household} \times FW_{proportion} \quad (4)$$

Where,

$FW_{proportion}$ = Proportion of HH fuel wood consumed by cooking stove. Use 41.50% for cooking application

$B_{old,caption}$ = Average baseline fuel wood consumption in tones per capita per year

$$B_{old,caption} = \frac{HC_{fuel\ wood,usage,y}}{HC_{population,y}} \quad (5)$$

Where, $HC_{fuel\ wood,usage,y} = 58,134,125$ t/year

$HC_{population,y} = 84,320,987$ [17]

$B_{old,caption} = 0.689$ t/year for fuel wood

$HC_{fuel\ wood,usage,y}$ = fuel wood consumption in cubic meter
 × wood density

fuelwood consumption in cubic meter = 80,185,000 m³ [51]

$$\text{wood density} = \frac{0.727\text{t}}{\text{m}^3}$$

2.5.2. Measurement of PM_{2.5} and CO in the Hood

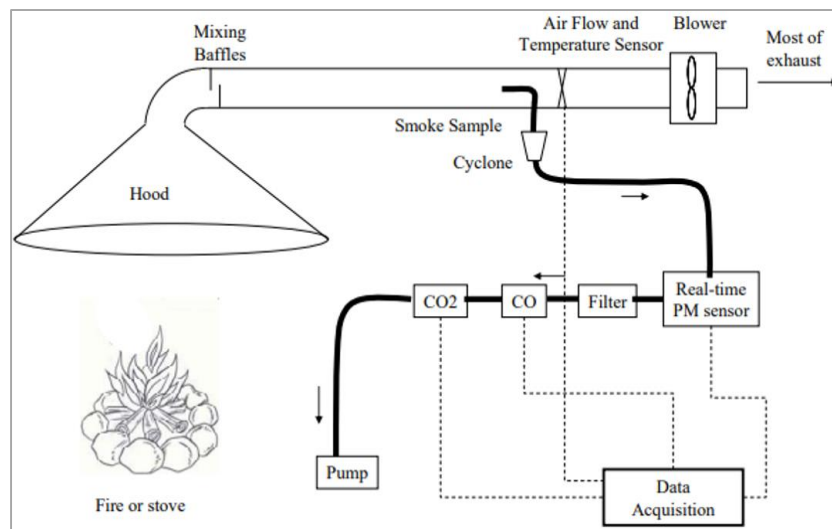


Figure 2. Setup for testing emissions.

The measurement of $PM_{2.5}$ is conducted with portable air detector that put inside the hood (Figure 2). Hood system is widely used for testing the small cooking stove without a chimney. Hood method helps to capture all the exhaust in a hood, and measure the flow rate through the hood. The $PM_{2.5}$ is collected using the detector that measure $PM_{2.5}$ and the values were recorded manually. The measurement system includes two parts: a flue gas analyzer (testo330-2LL) that directly sampled gas and measured real-time concentrations of CO and GHGs.

Total Emission Test

To measure the total emission GHGs, the stove was kept inside a closed standard hood, Figure 2. The hood had an overall dimension of 1000 mm width $\times$ 750 mm length $\times$ 2820 mm height. It has gas mixing chamber with 330-2 LL model multi component gas analyzer. Readings of CO and CO_2 were taken within 3 minutes interval [26].

2.6. Ethics Declarations

All procedures performed in studies involving human participants were in accordance with the ethical standards of Gambella University Institutional Research Committee. The study was approved by Institutional Review Board. Informed

consent was obtained from all individual participants included in the study.

3. Results and Discussion

3.1. Greenhouse Gas (GHG) Emission Reduction Potentials of IBCS

3.1.1. Estimation of the Carbon Dioxide (CO_2) Emission Reduction

The potential CO_2e emissions avoided by each stove was calculated assuming the net calorific value of fuel-wood (air-dried) at 15 MJ/kg (Hall *et al.*, 1994) and emission intensity of 109.7 g CO_2e /MJ of fuelwood burned in traditional stoves [25]. The total CO_2 emission reduction per stove per year was significantly different between the traditional and improved stoves. CO_2 emission reduction potential from ICSs were shown in Figure 3 which was taken from the estimate of CO_2 reduction calculated using the AMS-II G methodology [50]. The emission reduction potential of each IBCSs in terms of carbon credit saving was calculated as by using equation (1).

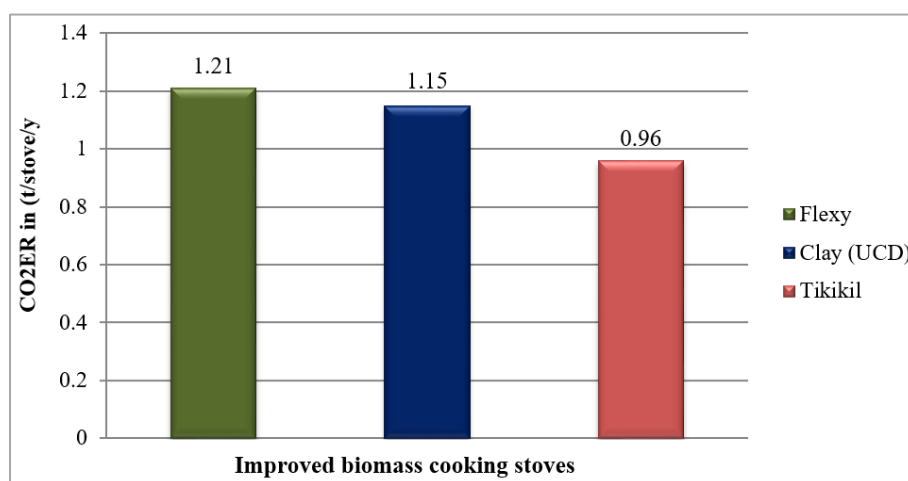


Figure 3. CO_2 emission reduction potential of improved biomass cooking stoves.

The result indicated that Flexy, Clay and Tikikil reduced the carbon emissions by 1.21 tCO_2 /stove/year, 1.15 tCO_2 /stove/year and 0.96 tCO_2 /stove/year respectively (Figure 3). These mean that, ICSs reduced carbon emissions by an average of 1.1 tCO_2 /stove/year. Flexy stove reduced carbon emissions by 36.44% than Clay stove (34.64%) and Tikikil stove (28.92%). The amount of CO_2e reduction using ICSs was found with in the range of CRGE strategy document, which is the abatement potential of 0.6–1.4 t CO_2e per stove per year, depending on the stove type. If we extrapolate the result of CO_2 emission reduction from the Ethiopian target to

disseminate 31 million ICSs by 2030 (considering 50% each Flexy, Clay and Tikikil), around 17.05 million CO_2e per year will be reduced. The result is in line with other similar studies [8, 14, 21, 33, 35, 53]. Additionally, the result is most approximately consistent with the finding of World Vision Ethiopia [57] who reports ICSs emit 1.14t CO_2 /stove/year. The CO_2 emission reduction potential of IBCS stove was within the range of the CRGE strategy documents which is the abatement potential of 0.6 – 1.4 t CO_2e /stove/year, depending on the stove type [18]. Furthermore, the result is also in line with DGB Group [13] who finds that energy-efficient cookstove

reduces CO₂ emissions by 2.85 tonnes annually compared to traditional open-fire cooking.

The results suggest that compared to the traditional stove, the three ICSs can reduce household CO₂e emissions substantially. Furthermore, this finding suggest that beyond fuel-wood savings, ICSs can have substantial potential for abating CO₂ emissions, thereby assisting Ethiopia's low-carbon economic development path and the global GHGs emissions reduction effort. Moreover, the large CO₂ emission savings from improved stoves indicates to generate revenue from carbon credits for emission reductions under the United Nations Clean Development Mechanism (CDM) and other international Green Climate Funds by expanding ICSs programs in different parts of Ethiopia.

3.1.2. Measurement of Carbon Monoxide (CO)

Carbon-monoxide was chosen as indoor air pollutants to be measured since it has been associated with respiratory and cardiovascular health effects. Wood-burning produced extremely high emissions of CO and other gasses. CO concentrations during the water boiling experimental test of Flexy, Clay, Tikikil and TCS were measured separately (Table 1). From the

finding it can be indicated that the CO emission from the three-stone stove was higher than that of the ICSs. The average amount of CO emission from the three-stone stove was 1105 ppm and from ICS was 370.3 ppm (Figure 4). Uncontrolled situations in the three-stone cookstove are the main contributor for higher CO concentrations. Flexy and Clay stove emitted significantly lower CO than the traditional cookstove. IBCSs reduced CO concentrations by 66.48% over the TCS. Less controlled combustion in the TCS is the main contributor to higher CO concentration. Even though each stove has its exclusive behavior, fuel feeding has two direct effects *i.e.*, decreasing the flame temperature and at the same time increasing CO. Adding solid fuel during the stove operation makes a sharp increase in CO emission. On the other hand, air supply in the IBCSs through the fuel magazine and ash grate assured higher combustion efficiency and lower pollutant emissions. However, the emission levels of CO during burning biomass are significantly impacted by fuel moisture content and stove design. Solid fuels with inefficient TCS are an important source of severe Household Air Pollution (HAP) linked to many adverse health problems.

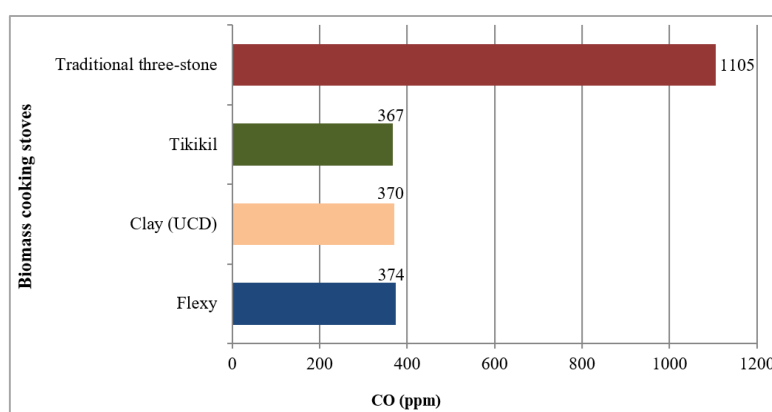


Figure 4. CO in ppm of biomass cooking stoves.

According to international standard for the Determination of Toxicity of Gases [38], CO will not be considered as toxic if its concentration in the atmospheric air doesn't exceed 4,947 ppm. However, a person near the stove felt health problems like headache, nausea and dizziness. Thus, IBCSs can significantly reduce household exposure to indoor-air pollution resulting from the burning of biomass fuels compared to

traditional stoves. Although Flexy, Clay and Tikikil stoves emitted relatively less CO than the traditional stove, the emissions from these ICS were above the proposed benchmark value of 20 g [31]. The result is supported by studies [1, 22, 35, 48]. Similarly, Mamuye F. *et al.* [32] reported that ICSs emit less amounts of CO as compared to traditional stove.

Table 1. Emission of Carbon Monoxide (CO).

Parameter	Type of biomass cookstoves			
	Flexy	Clay (UCD)	Tikikil	TCS
Emission of CO in ppm	517	547	679	1187

Parameter	Type of biomass cookstoves			
	Flexy	Clay (UCD)	Tikikil	TCS
	692	697	554	1876
	704	619	479	1834
	532	548	483	1621
	471	374	421	1460
	372	329	313	1345
	231	268	294	1213
	143	163	208	205
	54	96	142	168
	24	59	97	141
Average	374	370	367	1105

Source: Lab. Experiment result, 2022

3.2. PM_{2.5} Emissions from Biomass Cooking Stoves

The PM_{2.5} of each biomass cooking stoves was taken the average emitted in one hour by the interval of 5 minutes. From the result the PM_{2.5} emissions of Flexy, Clay, Tikikil and TCS were recorded 327, 341, 338, 614 mg respectively (Figure 5). The fine PM emissions from both improved stoves and the traditional stove were quite below the proposed benchmark value of 1500 mg [43]. The same to CO, the emission levels of PM_{2.5} during burning biomass are significantly impacted by fuel moisture content and stove design. From this finding,

PM_{2.5} emission reduction by Flexy, Clay, and Tikikil stoves were 34.33, 32.66 and 33.01%, respectively as compared with traditional cookstoves. Three stone stove releases high amount of PM_{2.5} than ICS which pollutes the environment more seriously. On the other hand, Flexy has a less impact on surrounding environment in terms of emitting PM followed by Clay and Tikikil cookstoves. Thus, it is better to use Flexy stoves for the refugees to have safe environment in terms of particulate matter or it is advisable to avoid using TCS to keep the surrounding environment clean from any particulate matter. The result is in line with other findings by Mamuye *et al.* [32] and Mekonnen [35] who reports PM_{2.5} concentration from the TCS was significantly higher than that of the IBCSs.

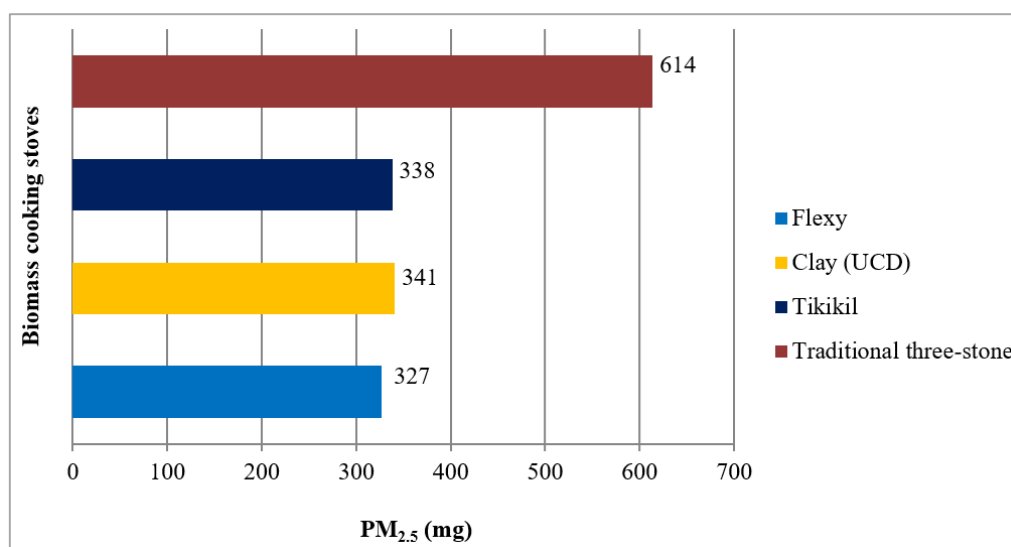


Figure 5. The PM_{2.5} emissions of biomass cooking stove.

The use of biomass, in fact, also produces emissions that are potentially harmful to health in the form of CO and PM_{2.5}. The smaller the size of the PM_{2.5} is the higher the potential impact on health. Thus, from the result, we can conclude that households will be exposed more to toxins that cause respiratory diseases due to inhaling smoke if they still use TCS. Clean cookstoves which burn fuels efficiently can reduce smoke emissions (PM_{2.5}), so that can significantly reduce the health risks of women and children.

4. Conclusion

The study was aimed to evaluate the potentials of improved biomass cookstoves in greenhouse gas emission reduction and compare them with three stone traditional cookstove based on experimental analyses through water boiling test (WBT) at laboratory level. The results indicated a significant reduction in greenhouse gasses and/or pollutants (CO₂, CO and PM_{2.5}) concentrations by the use of improved biomass cookstoves. Based on comparisons, the use of one Flexy stove could avoid the emission of 1.21 tons, Clay 1.15 tons, and Tikikil 0.96 tons of CO₂e per stove per year. The average amount of CO emission from the three-stone stove was 1105ppm and from ICS was 370.3 ppm in average. Particulate matter (PM_{2.5}) emissions of Flexy, Clay, Tikikil and Traditional cookstoves were recorded as 329, 339, 337, 614 mg respectively. The results indicated that shifting from traditional to improved cookstoves could mitigate CO₂, CO and PM_{2.5} emissions. From the result, it is concluded that improved biomass cookstoves significantly reduce carbon emissions, whereas traditional cookstoves have high emissions that lead to climate change. Thus, it is advisable to promote and advertise for widely distribution of these improved biomass cooking stoves. Distributing energy-saving cooking stoves as a sustainable, eco-friendly energy solution for households in Gambella refugee camps and to Gambella town communities as well is also very crucial.

Abbreviations

CDM	Clean Development Mechanism
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
CO ₂ e	Carbon Dioxide Equivalents
CRGE	Climate Resilient Green Economy
GHG	Greenhouse Gas
GoE	Government of Ethiopia
IBCS	Improved Biomass Cook Stoves
ICS	Improved Cook Stoves
MEI	Moving Energy Initiative
MoWIE	Ministry of Water, Irrigation and Energy
PM _{2.5}	Fine Particulate Matter
TCS	Traditional Cookstoves

UCD	User Center Design
WBT	Water Boiling Test

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Author Contributions

Fikre Destaw: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing

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Amansisa Birhanu: Data curation, Investigation, Supervision, Validation, Writing – original draft, Writing – review & editing

Nyagoo Biel: Data curation, Investigation, Supervision, Validation, Writing – original draft, Writing – review & editing

Girma Tadesse: Data curation, Investigation, Supervision, Validation, Writing – original draft, Writing – review & editing

Kuey Peter: Data curation, Investigation, Supervision, Validation, Writing – original draft, Writing – review & editing

Data Availability Statement

The datasets used and/or analyzed during the study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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