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RESEARCH

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Performance comparison of three prototype biomass stoves with traditional and *Mirt* stoves for baking *Injera*

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Abstract

Background *Injera* is food consumed daily by Ethiopians like bread and rice in other parts of the world. Biomass stoves are used to bake *Injera* in most rural households. The unsustainable use of fuelwood causes deforestation. Improved cook stoves such as *Mirt* (name in local language) were introduced to replace traditional stoves and save fuel wood. This study presents a performance comparison of three newly developed prototype biomass stoves with traditional and *Mirt* stoves. The prototype stoves were made with a clay pan (designated MUC: Mekelle University prototype with clay pan), with a glass pan (MUG) and with an aluminum pan (MUA). Controlled cooking tests were conducted for each type of stove to determine the thermal efficiency and specific fuel consumption.

Results The thermal efficiencies of the traditional, *Mirt*, MUC, MUA and MUG stoves were found to be 14%, 17%, 21%, 29% and 32%, respectively. Similarly, the percentage fuel wood savings by *Mirt*, MUC, MUA and MUG compared to the traditional stove were 32%, 48%, 64% and 67%, respectively. The results indicate that the prototype stoves had significantly better performance compared to the traditional and *Mirt* stoves.

Conclusion The prototype stoves have the potential to reduce fuel wood consumption by more than half of that currently consumed employing traditional stoves. In addition to the economic benefit of saving fuel wood, the improved stoves will have significant environmental implication. Based on the fuel saving figures, it is estimated that 0.4, 0.5 and 0.52 tons/year of fuel wood may be saved per household adopting MUC, MUA and MUG stoves, respectively.

Keywords Improved cook stoves, *Injera* baking, Controlled cooking test, Fuel savings, Thermal efficiency

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Background

Many people in developing countries of sub-Saharan Africa (SSA) and Asia use biomass as a dominant cooking fuel in traditional and inefficient stoves. Although biomass is a renewable energy source, unsustainable use leads to deforestation and its consequences. Many countries including Ethiopia lost their forests as trees were consumed as firewood, contributing to climate change. Inefficient stoves have also contributed to health hazards to users due to indoor pollution [1]. Universal access to clean cooking is one of the sustainable development goals (SDG 7) to be achieved by 2030. However, according to a report by the International Energy Agency, IEA [2], during the past decade (2010 to 2020), the number of people without access to clean cooking significantly increased in sub-Saharan Africa. The same report estimates the population without access to clean cooking to be over 1 billion in 2030. This implies that many households in SSA will be dependent on biomass in the coming decade. It is, therefore, essential that work on improving the performance of biomass stoves should concurrently be carried out with work on providing access to clean cooking.

Improved cook stoves (ICS) reduce fuel wood consumption and hence reduce the rate of deforestation and emissions to the environment. The adoption of ICS and performance comparisons with traditional stoves have been reported in literature worldwide. Comprehensive reviews on biomass cook stoves have been reported by Urmee and Gyamfi [3], Sutar et al. [4], Mehetre et al. [5] and Ahmad et al. [6]. The experience in India and the national programs for improved cook stoves in the last four decades have been discussed by Aggarwal and Chandel [7]. Performance comparisons of ICSs with traditional stoves have been reported in different countries, such as Wang et al. [8] in China, Rasoulkhani et al. [9] in Iran, Ochieng et al. [10] in Kenya and Grimsby et al. [11] in Tanzania. Wang et al. [8] conducted an experimental comparison of a traditional biomass stove made from brick with an ICS made of steel. It was reported that the thermal efficiency was improved by 31%. Rasoulkhani et al. [9] employed water boiling tests and found an improvement of approximately 22% in thermal efficiency by ICS compared to traditional stoves. Ochieng et al. [10] employed kitchen performance tests in households in rural communities and statistically compared the fuel consumption of ICS and traditional stoves. The results indicated that the ICS provided approximately 24% fuel savings. The study by Grimsby et al. [11] assessed biomass cook stoves by employing water boiling tests. The study found that some of the stoves sold as ICS were not significantly better than the traditional stoves, which indicates the need for thorough testing of ICS before dissemination.

In Ethiopia, approximately 90% of the energy used for cooking comes from biomass [12]. Baking *Injera*, a common food all over the country, accounts for a significant percentage of the biomass spent in a household. The three-stone open fire stove is still in use in many places in the country. However, there are also some traditional stoves that have been improved over generations. An example is the traditional Tigray stove (called *Mogog*o in local language) shown in Fig. 1a. The traditional Tigray stove is an enclosed cylindrical shape made from stone and mud with openings at the front and back. The front opening is for putting firewood into the stove, while the small opening on the upper part on the back acts as a chimney. The baking plate is a circular clay pan with a highly polished black surface placed on top of the stove and sealed all around. During baking, the plate is covered with a conical lid (called *Mugdi*) made from a mixture of soil and dung. The enclosure and sealing around the pan significantly reduced heat losses compared to the open fire stove. The opening at the front and an outlet at the back facilitated combustion of the wood fuel. The traditional Tigray stove was therefore a significant improvement from the three-stone open fire stove. If the three-stone open fire for baking Injera is considered as in the first-generation stoves, the traditional Tigray stove is in the second-generation stoves.

Mirt (meaning the best in local language) stoves (Fig. 1b) were introduced as part of an improved cook stove program in Ethiopia in the 1990s [13]. It was

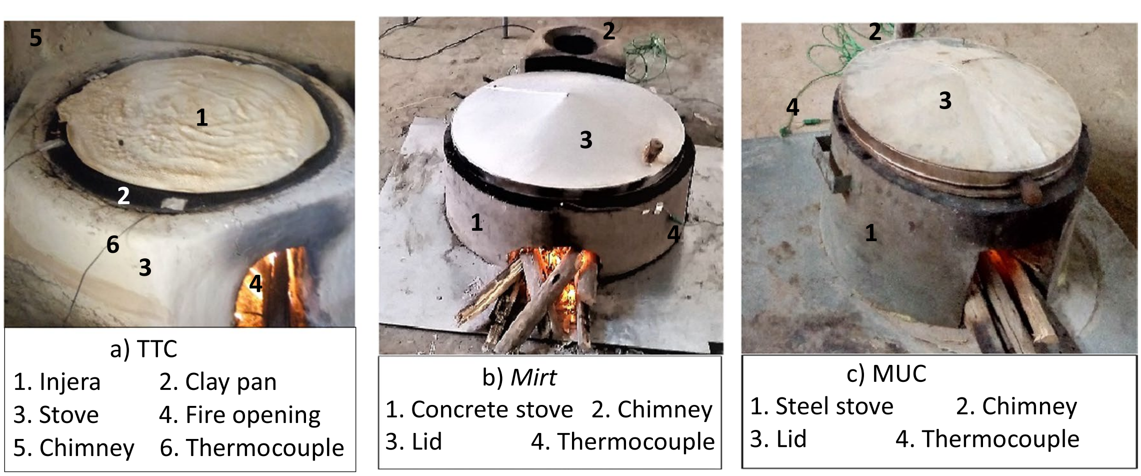

Fig. 1 Stoves under controlled cooking tests: **a** traditional Tigray stove, **b** Mirt stove and **c** MU prototype stove

developed to replace the three-stone open fire stoves widely used in the country at that time. It is an enclosed stove made from concrete with specified dimensions. Following the previous suggestion, *Mirt* stoves can be considered as in the third-generation stoves. Since the 1990s, most studies on biomass stoves for baking *Injera* have focused on estimating fuel wood savings, emissions and pollution reduction and identifying implementation challenges of the *Mirt* stove.

Fuel wood saving performance comparisons of the *Mirt* stove with the three-stone open fire have been made by different researchers at different locations in the country. The percentage of fuel savings reported varies between 20 and 40%. Dresen et al. [14] reported fuel savings of 39% based on controlled cooking tests (CCTs) in 14 randomly selected households in a village in southern Ethiopia. Zenebe et al. [15, 16] reported fuel savings of 22–31% based on CCTs conducted in 504 households in selected villages across three regional states. Recent studies by Yibeltal and Andaramola [17], Tiruwork et al. [18] and Ashenafi et al. [19] reported 30%, 31% and 35% fuel savings, respectively. The variation could be due to many factors during the cooking tests, but all studies agree on significant fuel wood savings by the *Mirt* stove compared to the traditional stove. The studies by Dresen et al. [14], Yibeltal and Andaramola [17] and Ashenafi et al. [19] estimated the potential emission reduction due to adoption of the *Mirt* stove to be 1.1, 2.8 and 0.7 t CO_2e per stove per year, respectively. Their estimations were based on the potential fuel savings per stove in a year, fraction of nonrenewable biomass (f_{NRB}), net heating calorific value (NCV) of biomass and assumed emission factor (EF). All three studies used the default values NCV = 15 MJ/kg and EF = 112 g CO_2e/MJ as per International Protocol for Climate Change guideline [20]. However, Dresen et al. used the estimated value $f_{NRB}=0.5$, Yibeltal and Andaramol assumed 1.0, and Ashenafi et al. used $f_{NRB}=0.88$. The variation in the potential emission reduction was due to their estimation of the fuel savings and the value of the f_{NRB} considered in their calculations.

A review of the literature by Kamil and Demiss [13] discussed different technologies and energy sources for *Injera* baking stoves. There are studies on electrical *Injera* stoves to reduce power consumption for urban dwellers employing electricity (Mesele et al. [21]; Hiwot [22]). There are also studies conducted on biogas *Injera* stoves (Derese [23]) and solar energy *Injera* stoves as alternative technologies (Abdulkadir [24]; Asfafaw et al. [25]; Mesele et al. [26]). However, there was no attempt to further improve the performance of the biomass stove after the intervention in the 1990s. The current study was initiated to investigate improving the performance of the biomass stove by examining the geometrical dimensions and material of construction of the stove and the baking pan (Fig. 1c).

The current study proposes fourth-generation biomass *Injera* baking stoves. The novelty of the prototypes under study was the use of materials different from the previous generation of stoves reviewed. Three prototypes with the same stove dimensions but different baking plate materials were experimentally tested. The material used for the construction of the stoves was mild steel due to its availability and low cost. Clay, aluminum and glass were the materials used for the baking plates. Clay was tested to keep the traditional baking pan and investigate the improvement due to only the change in the new prototype stove. Due to its very good thermal property aluminum has been used to replace the clay pan. The prototype with an Aluminum baking plate was used to demonstrate the potential of using metal as a baking plate for *Injera*. Stainless steel or any other metals safe for cooking may be used replacing Aluminum in further development of the stoves. Glass was the third material tested as a baking plate. Borosilicate glass was, therefore, used for the third prototype. The paper presents performance comparison of the three prototypes with *Mirt* and traditional Tigray stoves in terms of fuel savings, thermal efficiency, and reduction in emissions.

Methods

Description of the stoves

The descriptions of the five stoves tested in the study are summarized in Table 1. Commonly accepted size of *Injera* varies between 50 and 60 cm in diameter. Traditional stoves have variations in height, while the diameter is commonly approximately 60 cm. The diameter of 62 cm and height 32.5 cm shown in the table are for the stove tested in the experiments. The dimensions for *Mirt* stoves are consistent, as the stoves are produced under specification by trained persons. The three prototypes were developed at Mekelle University (MU) by the authors of this paper. The diameter of the stove was decided to be 50 cm to be within the accepted range of the size of *Injera*. The stove is made of two concentric cylinders with fiberglass in between designed to provide insulation. The prototypes employ the same stove but three different types of materials for the pan: clay, glass, and aluminum. The thickness of the clay pans was 2 cm, the aluminum pan was 1 cm, and the glass pan was 0.5 cm. The abbreviations shown in the table will be consistently used throughout the paper.

Description of the controlled cooking test

Preliminary tests were carried out for the operator to be accustomed to all the stove types before the CCT. The operator was already familiar with the traditional and

Table 1 Description of the five types of stoves tested

Stove type	Abbreviation	Stove material	Stove dimensions	Pan material	Pan thickness
Traditional Tigray clay pan	TTC	Stone and mud aggregate	Diameter 62 cm Height 32.5 cm	Clay	2 cm
Mirt	*Mirt*	Concrete aggregate	Diameter 60 cm Height 24 cm	Clay	2 cm
MU prototype clay pan	MUC	Mild steel	Diameter 50 cm Height 28 cm	Clay	2 cm
MU prototype glass pan	MUG	Mild steel	Diameter 50 cm Height 28 cm	Glass	0.5 cm
MU prototype aluminum pan	MUA	Mild Steel	Diameter 50 cm Height 28 cm	Aluminum	1 cm

Mirt stoves. Since the prototype stoves were new, the operator was trained on their use during the preliminary tests. Controlled cooking tests were conducted with three replications for each stove type, therefore, a total of 15 tests. The amount of batter baked, type and cut size of the fuel wood and test conditions were controlled. The amount of batter baked in each test was 16 kg. Eucalyptus tree wood branches cut to 50 cm in length and approximately 4 to 5 cm in diameter were used as fuel. The moisture content of samples of the fuel wood was measured during each test. The mass of fuel wood was weighed before feeding into the stove, any remaining fuel wood was accounted for, and the net consumption was recorded for each test. During ignition or the start of burning, small pieces of wood of approximately 200 g were used in every test. The tests were all conducted indoors with similar ambient temperatures (20–22 °C) and the same person operating the stoves.

Thermocouples (k-type) were installed at different positions, as shown in Fig. 2. Three thermocouples on the surface of the baking pan were used to obtain the average baking temperature. To investigate the heat loss from the stoves, a thermocouple was installed at the outer wall. The ambient temperature of the room was also measured during the tests. The remaining temperature sensors shown in the figure were not included in the data analysis of this paper. Temperature measurements were logged every second to a data logger (model Picolog TC-08). Temperature development with time during the initial heat up and during the baking cycles were observed for each type of stove. The temperature development during the tests for the five types of stoves were compared in terms of heat-up time (t_h), total time to complete baking (t_b), average temperature during the continuous baking cycles (T_{bc}) and the outer wall temperature (T_{ow}).

Performance comparisons

Comparison of the performance of the stoves was carried out based on specific fuel consumption and thermal efficiency. The specific fuel consumption (*S*fc) was determined by the ratio of the equivalent mass of dry fuel wood (m_{df}) to the total mass of batter (m_{bb}) baked

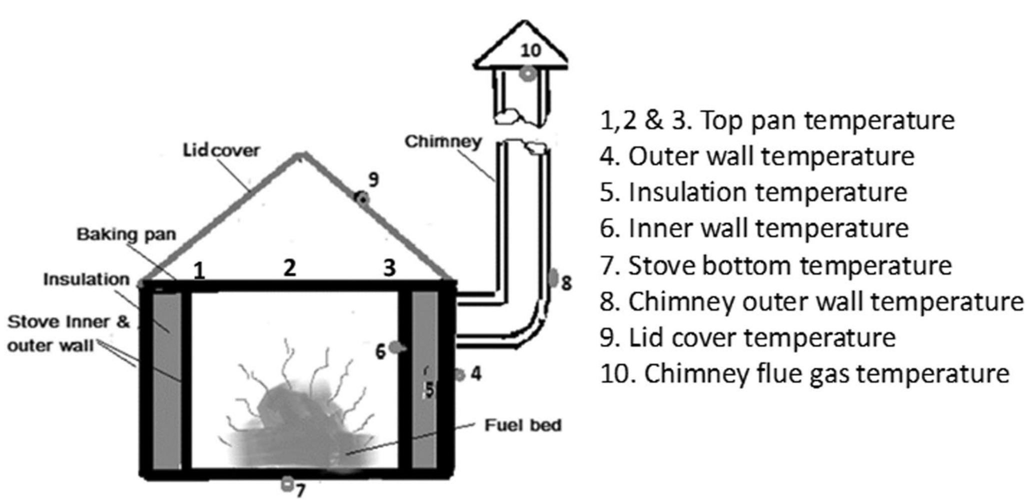

Fig. 2 Schematic drawing of a stove under test indicating the location of the thermocouples

during the test. During each test, the average moisture content (MC), mass of fuel wood consumed (m_{fc}) and mass of leftover char (m_{ch}) were measured. The equivalent mass of dry wood takes into consideration moisture content and amount of leftover char. Based on energy balance the equivalent mass of dry fuel wood (m_{df}) was found from Eq. 1:

$$NCV_{df}m_{df} = NCV_{df}m_{fc}(1 - MC) - m_{fc}MC\left(C_{pw}(T_b - T_a) + h_{fg}\right) - NCV_{ch}m_{ch}, \quad (1)$$

where NCV_{df} and NCV_{ch} are the net calorific heat values of eucalyptus dry wood and char, respectively; C_{pw} is the specific heat capacity and h_{fg} specific heat of vaporization of water; T_b and T_a are the water boiling temperature and ambient temperature at the test site. All these parameters are constant physical properties of eucalyptus and water, and temperature at the testing site. The values for NCV_{df} and NCV_{ch} were taken from studies made on different species of eucalyptus trees in Ethiopia reported in [27].

The values of the constant parameters were:
$NCV_{df} = 18000\frac{kJ}{kg}$; $NCV_{ch} = 30,000\frac{kJ}{kg}$; $C_{pw} = 4.2\frac{kJ}{kgK}$; $h_{fg} = 2260kJ/kg$; $T_b = 94°C$; $T_a = 20°C$.

Entering the constants indicated above, Eq. 1 was simplified into Eq. 2 as a function of the measured values of the mass of wood consumed (m_{fc}), moisture content (MC) and mass of char (m_{ch}):

$$m_{df} = m_{fc}(1 - 1.14MC) - 1.67m_{ch}. \quad (2)$$

The specific fuel consumption (*Sfc*) was then determined from Eq. 3:

$$Sfc = \frac{m_{df}}{m_{bb}}. \quad (3)$$

It can be noted from Table 1 that the size of *Injera* will be smaller in the prototypes ($D = 50$ cm) compared to *Mirt* (D = 60 cm) and the traditional stoves ($D = 62$ cm). Hence, no parameter comparisons will be made per *Injera* but with respect to the total mass of *Injera* baked.

Thermal efficiency (η_{th}) was determined from the ratio of the useful energy during baking to the amount of energy consumed as shown in Eq. 4. The useful energy during baking was the sum of the sensible heat to raise the batter from ambient temperature to boiling temperature and latent heat of the amount of water evaporated during the process. The amount of energy consumed was found from the product of the equivalent mass of dry fuel wood (m_{df}) obtained from Eq. 2 above and the net calorific heat value NCV_{df} :

$$\eta_{th} = \frac{m_{bb}C_{pb}(T_b - T_a) + m_{we}h_{fg}}{NCV_{df}m_{df}}, \quad (4)$$

where m_{bb} is mass of the batter, $C_{pb} = 3.2\frac{kJ}{kgK}$ is the heat capacity of the batter mixture (considering 70% water and 30% flour), T_b is boiling temperature,T_a is ambient temperature; m_{we} is mass of water evaporated and h_{fg} is specific heat of vaporization of water. The total mass of the batter m_{bb} and the mass of Injera at the end of baking were measured during the tests. The mass of water evaporated m_{we} was found by calculating the difference between the two measured values.

Estimation of potential fuel wood savings and emission reduction

The economic benefit of the stoves was assessed based on the potential fuel wood savings compared to the traditional stove. The fuel savings will have potential benefits in monetary terms for the households, pollution reduction, reduction in deforestation and reduction in greenhouse gases (GHG) emission. It was considered that one household would bake *Injera* twice a week (with 16 kg batter). The annual fuel wood savings of the *Mirt* and prototype stoves were determined compared to the annual consumption of the traditional stove. The calculations were carried out based on the average of the three baking tests conducted for each stove type. The amount of fuel wood savings of the ICS per stove per session B_{saving} was found from Eq. 5. The yearly fuel wood savings $B_{y,saving}$ were calculated by multiplying by the number of baking sessions in a year:

$$B_{saving} = m_{fc,TTC} - m_{fc,ICS}. \quad (5)$$

The percentage savings , P_{saving} compared to the traditional stove was calculated using Eq. 6:

$$P_{saving} = (m_{fc,TTC} - m_{fc,ICS})/m_{fc,TTC}. \quad (6)$$

The estimation of the potential for deforestation reduction was made at the Tigray region level. The region has more than 700,000 households [28] in rural areas employing traditional stoves. An overall estimate of the annual wood savings and the number of hectares of forest saved has been made considering only 20% of households adopt improved biomass technologies. A conversion factor of 125 tons of biomass per hectare was employed based on the study results of Mehari et al. [29] for eucalyptus forests in central Ethiopia, which ranged from 125 to 147 t/ha.

The potential fuel wood savings imply that there will be a potential for green house gas (GHG) emission reduction due to the introduction of the technologies. A guideline by the UNFCC Clean Development Mechanism (CDM) for estimating emission reduction due to the introduction of technologies has been employed. The recent version of the CDM, AMS-II, G version 13.0 guideline [30], suggests Eq. 7 to estimate the yearly emission reduction ER_y in t CO_2e (adapted here to a single technology):

$$ER_y = B_{y,saving} \times f_{NRB,y} \times NCV_{biomass} \times EF_{projected,\ fossil\ fuel}, \quad (7)$$

where $B_{y,saving}$ is the mass of fuel wood saved in a year in t/stove, $f_{NRB,y}$ is the fraction of nonrenewable biomass, $NCV_{biomass}$ is the net calorific value of the fuel wood in TJ/kg, and $EF_{projected,\ fossil\ fuel}$ is the projected fossil fuel that would substitute the woody biomass by similar consumers in t CO_2e/TJ. The guideline also suggests default values $NCV_{biomass}=0.0156$ TJ/t and $EF_{projected,\ fossil\ fuel}=73.2$ t CO_2e/TJ for the region of SSA. A value of $f_{NRB,y}=0.88$ has been used in the estimation based on the f_{NRB} country index for Ethiopia [31].

Statistical analysis and estimation of uncertainty

The controlled cooking tests were conducted for each type of stove with three replications. Parameters measured during tests, as mentioned in the previous sections include heat-up time (t_h), time to complete baking (t_b), temperature during baking cycles (T_{bc}), outer wall temperature (T_{ow}), mass of fuel wood consumed (m_{fc}), moisture content (MC), mass of char (m_{ch}) and mass of water evaporated (m_{we}). The average (X_{avg}) and standard deviation (SD) of the parameters measured were calculated from Eq. 8 and 9, respectively:

$$X_{avg} = \frac{\sum_{i=1}^{3} X_i}{3}, \quad (8)$$

$$SD = \sqrt{\frac{\sum_{i=1}^{3} \left(X_i - X_{avg}\right)^2}{2}}, \quad (9)$$

where X_i is measured value during the replication test (i) of the parameters listed above.

The uncertainty in the calculation of the thermal efficiency was determined from the standard deviation of the measured data of the mass of water evaporated (SD_{mwe}) and the mass of dry fuel wood (SD_{mdf}). By applying the principles of uncertainty propagation for a parameter obtained by division of two measured variables, the uncertainty in calculating the thermal efficiency was found from Eq. 10:

$$u_{\eta_{th}} = \eta_{th}\sqrt{\frac{\left(h_{fg} SD_{mwe}\right)^2}{\left(m_{bb} C_{pb}(T_b - T_a) + m_{we} h_{fg}\right)^2} + \frac{(SD_{mdf})^2}{(m_{df})^2}}. \quad (10)$$

The uncertainty in the percentage of savings was determined from the standard deviation of mass of fuel wood consumed by the ICS (SD_{mfcICS}) and that of the TTC stove (SD_{mfcTTC}). Similarly, from the principles of uncertainty propagation, the uncertainty in calculating the percentage of fuel savings was found from Eq. 11:

$$u_{saving} = P_{saving}\sqrt{\frac{(SD_{mfcTTC})^2 + (SD_{mfcICS})^2}{\left(m_{fc,TTC} - m_{fc,ICS}\right)^2} + \frac{(SD_{mfcTTC})^2}{(m_{fc,TTC})^2}}. \quad (11)$$

Results

Comparison of temperature development in the stoves during CCT

The temperature profiles for the traditional, *Mirt* and MUC stoves (with clay pans) during each test are shown in Fig. 3. From Fig. 3a and c, it can be observed that both the traditional stove and *Mirt* stove took an average heat-up time of approximately 20 min to reach an average baking surface temperature of 150 ℃. The average temperature for continuous baking cycles for the traditional stove was approximately 234 ℃, while for the *Mirt* stove, it was slightly higher at 251 ℃. On the other hand, the MUC prototype stove was slower in attaining the minimum average surface temperature of 150 ℃ with a heat-up time of 25 min, and the continuous baking average temperature was similar to that of the traditional stove at 235 ℃ as indicated in Fig. 3e.

In Fig. 3b, the outside wall temperature of the traditional stove during the tests increased continuously to a maximum of 150 ℃ and in Fig. 3d the temperature of *Mirt* stove increased to approximately 200 ℃. In the case of the MUC prototype stove, the temperature increased to 100 ℃ during the heat-up time and remained constant during the continuous baking cycles as shown in Fig. 3f.

Similarly, Fig. 4 shows the temperature profiles for the MUG and MUA stoves during the tests. The initial heat-up time for both stoves was within 10 min, significantly shorter than the clay stoves in Fig. 3. The average baking cycle temperature was approximately 185 ℃ for MUA and approximately 130 ℃ for MUG. Correspondingly, the outer wall temperature was approximately 60 ℃ for both stoves.

A summary of the results from Figs. 3 and 4 is shown in Table 2. The initial heat-up time was found to be significantly low for the MUG and MUA stoves. The surface

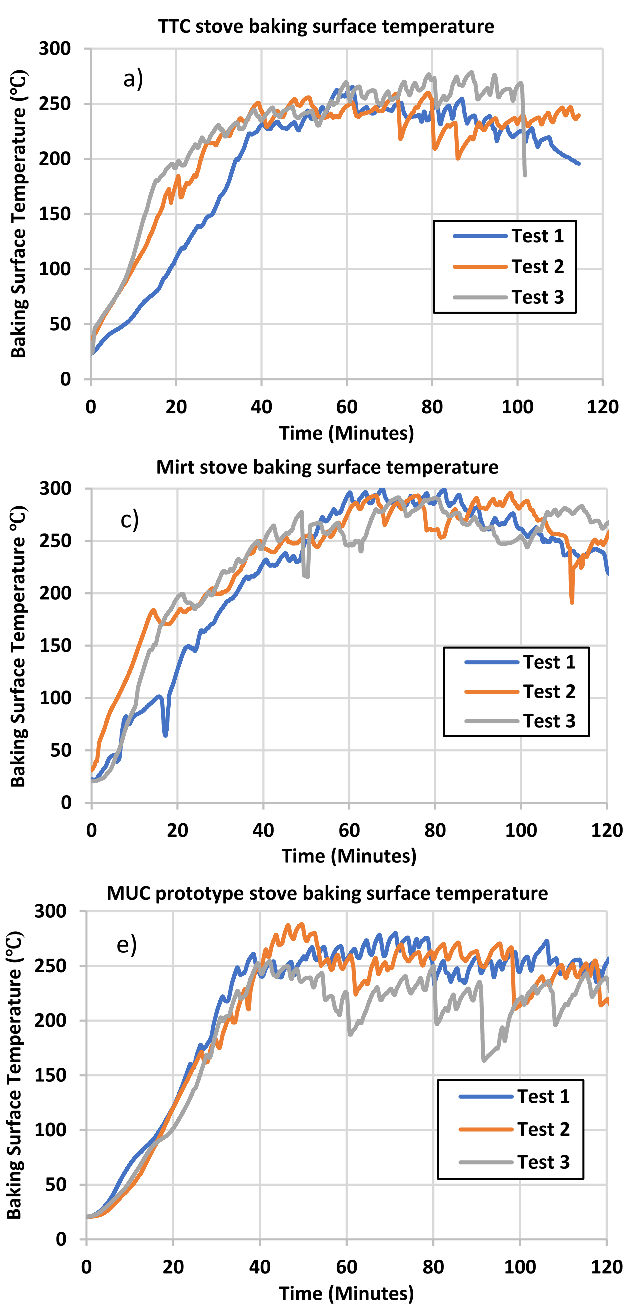

Fig. 3 Temperature development of the pan surface and outside wall for the TTC, Mirt and MUC stoves

temperature during the baking cycle was above 200 °C for the stoves with clay pan TTC, *Mirt* and MUC. It was possible to bake *Injera* at temperatures lower than 200 °C with MUG and MUA stoves. There was also a significant difference in the outside wall temperature of the stoves. The prototype stoves had significantly lower outside wall temperatures compared to the *Mirt* stove.

The overall baking time took approximately 2 h for the TTC, *Mirt* and MUA. The baking time was longer for the MUC and MUG stoves by approximately half an hour. Looking at the baking cycles of MUC, there were more idle times, especially in tests 1 and 2 (Fig. 3), and more cycles of baking (higher number of *Injera*) compared to the other stoves. Hence, the reason for the longer time for the MUC is probably due to operational reasons. For the MUG stove, the baking temperature was approximately 130 °C (Fig. 4), which resulted in every cycle taking more time for the *Injera* to fully bake (evaporate the necessary

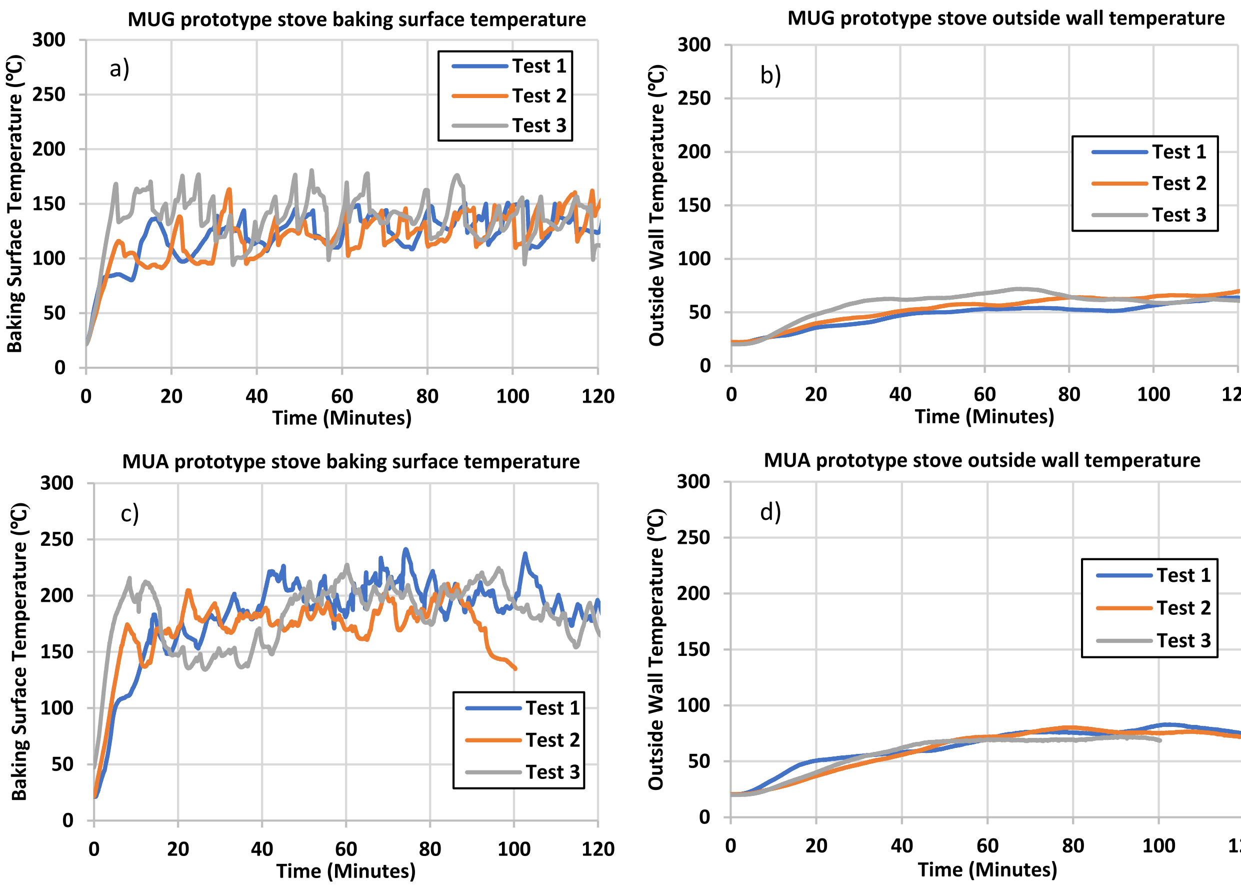

Fig. 4 Temperature development of the pan surface and outside wall for the MUG and MUA stoves

amount of water from the batter); hence, the total baking time was higher.

Performance comparison of the stoves during cooking-controlled tests

Cooking controlled tests were conducted as per the procedures described in previous section. Moisture content of fuel wood, mass of fuel wood consumed, and mass of char recorded for each stove type and test number are shown in the appendix as Table 8. The equivalent mass of dry wood m_{df} was calculated using Eq. 2 discussed in previous section. The specific fuel consumption (Sfc) was then calculated using Eqs. 3, with mass of batter $m_{bb} = 16$ kg, which was constant during all tests. Table 3 shows a summary of the average and standard deviation (SD) of the test results. The results indicate that the prototype stoves have significantly reduced specific fuel consumption compared to the traditional and *Mirt* stoves. The specific fuel consumption by the MUC stove (184 g/kg) was approximately half, while that of the MUG (131 g/kg) and MUA (117 g/kg) was approximately one-third compared to the traditional stove (349 g/kg).

The thermal efficiency of the stoves was also calculated based on Eq. 4 discussed in the methods section. The measured mass of water evaporated and the calculated equivalent mass of dry fuel for each stove type and replication test are shown in the appendix as Table 9. The respective useful baking energy, fuel wood energy consumed, and thermal efficiencies calculated using Eq. 4, for each stove type and test number are also indicated in Table 9. The summary of the average and standard deviation of the tests for each stove type is shown in Table 4. In terms of the thermal efficiency, the prototype MUC stove performed better than TTC and *Mirt* by 6% and 4%, respectively. The MUG and MUA stoves performed significantly better with 17% and 14% improvements in thermal efficiency compared to the traditional stove.

The uncertainty for the calculation of the thermal efficiency was determined using Eq. 10 of the methods section. The average and standard deviation of the equivalent mass of dry fuel wood and the mass of water evaporated for each stove from Table 9 were used in Eq. 10 to find the uncertainty. The uncertainties in

Table 2 Average temperatures and time during the controlled cooking tests

Stove	Replication	Initial heat-up time t_h (minutes)	Total baking time t_b (minutes)	Average surface temperature during baking cycle T_{bc} (°C)	Average stove outside wall temperature T_{ow} (°C)
TTC	1	26	115	229	98
	2	24	123	230	76
	3	24	104	242	93
	Average	25	114	234	89
	SD	1	10	7	12
Mirt	1	23	122	253	136
	2	20	139	249	137
	3	22	139	252	137
	Average	22	133	251	137
	SD	2	10	2	1
MUC	1	20	171	249	80
	2	19	154	238	85
	3	22	161	217	79
	Average	20	162	235	81
	SD	2	9	16	3
MUG	1	13	204	126	54
	2	9	157	126	58
	3	8	140	137	58
	Average	10	167	130	57
	SD	3	33	6	2
MUA	1	9	126	194	64
	2	10	124	176	62
	3	8	100	185	57
	Average	9	117	185	61
	SD	1	14	9	4

Table 3 Summary of performance data for baking (16 kg batter) sessions of the stoves under test

Parameter	TTC average (SD)	*Mirt* average (SD)	MUC average (SD)	MUG average (SD)	MUA average (SD)
Mass of fuel wood consumed (m_{fc}) [g]	7397 (422)	5000 (118)	3843 (169)	2660 (249)	2447 (97)
Equivalent mass of dry fuel wood (m_{df}) [g]	5587 (257)	3880 (171)	2938 (160)	2100 (191)	1876 (113)
Specific fuel consumption (*Sfc*) [g/kg]	349 (16)	243 (11)	184 (10)	131 (12)	117 (7)

Table 4 Summary results of thermal efficiency of the stoves under test

Parameter	TTC average (SD)	*Mirt* average (SD)	MUC average (SD)	MUG average (SD)	MUA average (SD)
Useful baking energy (MJ)	14 (0.1)	12 (0.4)	11 (0.4)	12 (0.2)	9 (0.9)
Fuel wood energy consumed (MJ)	101 (5)	70 (3)	53 (3)	38 (3)	31 (2)
Thermal efficiency (η_{th}) [%]	14	16	20	31	28
Uncertainty [%]	1	1	1	3	3

calculating the thermal efficiencies were within a range of 1–3%, as indicated in Table 4.

Estimation of fuel wood savings and emission reduction

The average food savings and percentage of savings of the improved cook stoves compared to the traditional stove were calculated using Eqs. 5 and 6. Table 5 shows summary results for *Mirt* and prototype stoves. The table indicates significant fuel wood savings by the *Mirt* stove and the prototype stoves. *Mirt* stove had 32% savings compared to the traditional stove. The prototype MUC had 48% savings, while MUG and MUA had 64% and 67% savings double the amount of savings of the *Mirt* stove.

The uncertainty of the calculation of the percentage fuel wood savings was carried out using Eq. 11. The respective average and standard deviation of the equivalent mass of dry wood for each stove type as shown in Table 8, was used to calculate the uncertainty. The uncertainties were found to be in the range of 6–8% as shown in Table 5.

The estimation of annual fuel wood savings at the household level and extrapolated over the Tigray region levels are shown in Table 6. *Mirt* and MUC stoves have potential household level savings of 0.25 and 0.4 tons per year, respectively. The MUG and MUA stoves have twice that of the savings by *Mirt,* with approximately 0.5 tons per year. At the regional level with an estimated 700,000 households, considering 20% of the households adopting the new technologies, annual fuel wood savings would be in the range of 56,000 to 72,800 tons. The equivalent forest area saved per year is estimated to be between 450 and 580 hectares.

The potential GHG emission reduction per ICS per year based on Eq. 7 and estimation at the regional level are shown in Table 7. The value for the fraction of nonrenewable biomass $f_{NRB,y'}=0.88$ and default values of the net calorific value of the fuel wood, $NCV_{biomass}$ and the emission factor, $EF_{projected,\ fossil\ fuel}$ were employed in the calculation. With these values, the conversion between tons of fuel wood saved and tons of carbon dioxide equivalent emission reduction becomes a factor of approximately 1.0. One ton of fuel wood saved implies approximately one ton of carbon dioxide equivalent emission reduction. The regional estimation indicates that with 20% of households adopting the *Mirt* stove, approximately 35,000 tons of carbon dioxide equivalent emissions can be reduced annually. With the introduction of prototype stoves considering similar 20% households adopting the technology, annually, between 56,000 and 72,800 tons of carbon dioxide equivalent emissions can be reduced.

Table 5 Fuel wood savings of the *Mirt* and the prototype stoves per baking session

Parameter	*Mirt*	MUC	MUG	MUA
Average fuel wood savings (B_{saving}) per stove per session [g]	2397	3843	4737	4950
Percentage savings [%]	32	48 7	64	67
Uncertainty [%]	6		8	7

Table 6 Estimation of annual fuel wood savings at the household level and over the region

Parameter	*Mirt* Average	MUC Average	MUG Average	MUA Average
Fuel wood savings ($B_{y,saving}$) per household per year [ton]	0.25	0.40	0.50	0.52
Regional savings per year [ton]	35,000	56,000	70,000	72,800
Regional forest saved per year [ha]	280	450	560	580

Table 7 Potential GHG emission reduction per household and over the region

Parameter	*Mirt* Average	MUC Average	MUG Average	MUA Average
Emission reduction per stove per year [t CO_2e]	0.25	0.40	0.50	0.52
Regional emission reduction per year [t CO_2e]	35,000	56,000	70,000	72,800

Discussion

Improvement in stove heat-up time, baking surface and external wall temperatures

The results obtained from the temperature development during the CCT provided insights into the performance of the stoves. The prototype stoves MUG and MUA with their glass and aluminum pans, exhibited shorter heat-up times compared to the clay pan stoves (TTC, *Mirt* and MUC). The MUG stove, with its thin glass pan, and the MUA stove, with its highly thermally conductive aluminum pan, were able to reach the desired baking temperatures in half the time required by the clay pan stoves. Furthermore, the average surface temperature during the baking cycles were different among the stove types. The stoves with clay pan operated at temperatures above 200 °C while the MUG and MUA stoves were able to bake Injera at lower temperatures, below 200 °C. The difference in baking cycle temperatures was influenced by the need to maintain the quality of *Injera*. The stoves with clay pans required higher temperatures to achieve the desired *Injera* quality, while temperatures exceeding 200 °C in the MUG and MUA stoves resulted in a deterioration in the quality of the baked *Injera*. On the other hand, the baking time for the prototype stoves was longer than the traditional and *Mirt* stoves. The baking time for the 16 kg batter for the MUG stove was longer by half an hour than the traditional and *Mirt* stoves. In practical terms, for households conducting two baking sessions per week, this translated to only an additional hour spent on baking *Injera*.

The external wall temperature of the stoves also provided a clear indication of the extent of heat losses. The prototype MUC stove maintained a lower maximum external wall temperature of about 100 °C compared to TTC (150 °C) and *Mirt* (200 °C). The prototype MUG and MUA stoves exhibited even lower external wall temperatures of around 60 °C. Consequently, the prototype stoves demonstrated reduced heat losses when compared to the traditional and *Mirt* stoves. This reduction in heat loss was made possible by the design of insulation in the prototype stoves and the lower-temperature baking cycles in the case of the MUG and MUA stoves.

Implication for thermal efficiency and fuel savings

Comparison of the stoves in terms of thermal efficiency and fuel savings implied that the prototype stoves had significant improvement in performance. The MUC prototype stove had 20% thermal efficiency surpassing the counterpart clay pan traditional and Mirt stoves by 6% and 4%, respectively. With the change of the clay pan to aluminum MUA and glass MUG, the thermal efficiency was further improved to 28% and 31%, respectively. The thermal efficiency figures indicated double that of the traditional stove. These promising results can be attributed to the design of prototypes, which incorporate insulation and replacement of the traditional clay pan with materials such as thin glass and aluminum (or other suitable metals like stainless steel).

As the result of the improved efficiency the fuel wood savings by the prototype stoves was significant. The percentage of fuel wood savings by *Mirt* stove compared to the traditional stove was 32%. This result was in the range of values previously reported in literature by Yibeltal and Muyiwa [17], Tiruwork et al. [18] and Ashenafi et al. [19]. The prototype clay pan stove (MUC) performed better than the *Mirt* stove with 48% savings compared to the traditional stove. The percentage fuel wood savings compared to the traditional stove by MUG and MUA were 64% and 67%, respectively. The improvement due to the change of the pan from clay to aluminum or glass resulted in about 20% further fuel wood savings.

Implication for reduction of deforestation and GHG emissions

Estimation of the potential reduction in deforestation considering 20% of the households in the Tigray region adopting the new technologies indicated that more than 56,000 tons per year of fuel wood could be saved. This would be equivalent to more than 450 hectares of forest saved every year. By applying the UNFCC guideline for estimating the potential GHG emission reduction due to savings in biomass, it would be equivalent to more than 56,000 tons of CO_2e emission reduction every year.

Conclusions

The three prototype stoves with clay, glass, and aluminum pans exhibited remarkable performance improvements when compared to both the *Mirt* and traditional clay pan stoves. This enhanced performance was primarily attributed to the innovative design features of the prototypes, which included insulation and the substitution of traditional clay pans with glass and aluminum materials. These modifications not only accelerated the heat-up process, but also sustained lower baking temperatures without compromising the quality of the baked *Injera*. This combination effectively minimized heat losses. Consequently, the prototype stoves demonstrated significantly higher thermal efficiency compared to traditional stoves. This increased efficiency translated into substantial fuel wood savings, making the prototype stoves more environmentally friendly and cost-effective for households.

The adoption of these improved stove technologies has the potential to reduce deforestation significantly. If widely adopted, these stoves could save a substantial amount of fuel wood, equivalent to preserving a substantial area of forest. Additionally, the reduction in fuel wood consumption contributes to a significant reduction in greenhouse gas emissions, aligning with efforts to combat climate change.

Appendix

See Tables 8 and 9

Table 8 Test data during CCT and calculated performance parameters

Stove	Replication	Mass of batter (m_{bb}) [kg]	Mass of fuel wood consumed (m_{fc}) [g]	Mass of char (m_{ch}) [g]	Moisture content (*MC*) [%]	Equivalent mass of dry fuel wood (m_{df}) [g]	Specific fuel consumption (*Sfc*) [g/kg]
TTC	1	16	7870	330	16	5883	368
	2	16	7260	290	16	5451	341
	3	16	7060	207	16	5427	339
	Average	16	7397	276	16	5587	349
	SD		422	63	0	257	16
Mirt	1	16	4970	116	15	3926	245
	2	16	5130	172	14	4024	252
	3	16	4900	189	16	3691	231
	Average	16	5000	159	15	3880	243
	SD		118	38	1	171	11
	Savings		2397				
	Percentage		32%				
	Uncertainty		6%				
MUC	1	16	3960	110	16	3054	191
	2	16	3920	146	15	3006	188
	3	16	3650	137	16	2755	172
	Average	16	3843	131	16	2938	184
	SD		169	19	1	160	10
	Savings		3553				
	Percentage		48%				
	Uncertainty		7%				
MUG	1	16	2880	32	17	2268	142
	2	16	2710	27	17	2140	134
	3	16	2390	21	17	1892	118
	Average	16	2660	27	17	2100	131
	SD		249	6	0	191	12
	Savings		4737				
	Percentage		64%				
	Uncertainty		8%				
MUA	1	16	2530	93	15	1942	121
	2	16	2470	81	14	1941	121
	3	16	2340	100	16	1746	109
	Average	16	2447	91	15	1876	117
	SD		97	10	1	113	7
	Savings		4950				
	Percentage		67%				
	Uncertainty		7%				

Table 9 Thermal efficiency of baking

Stove	Replication	Mass of batter (m_{bb}) [g]	Mass of evaporated water (m_{we}) [g]	Useful baking energy [MJ]	Equivalent mass of dry fuel wood (m_{df}) [g]	Fuel wood energy consumed [MJ]	Thermal efficiency (η_{th}) [%]	Uncertainty u_{th}[%]
TTC	1	16000	4407	14	5883	106	13	
	2	16000	4409	14	5451	98	14	
	3	16000	4449	14	5427	98	14	
	Average	16000	4422	14	5587	101	14	
	SD	0	24	0	257	5		1
Mirt	1	16000	3106	11	3926	71	15	
	2	16000	3443	12	4024	72	16	
	3	16000	3414	12	3691	66	17	
	Average	16000	3321	11	3880	70	16	
	SD	0	187	0	171	3		1
MUC	1	16000	3125	11	3054	55	20	
	2	16000	2791	10	3006	54	19	
	3	16000	3142	11	2755	50	22	
	Average	16000	3019	11	2938	53	20	
	SD	0	198	0	160	3		1
MUG	1	16000	3508	12	2268	41	29	
	2	16000	3666	12	2140	39	31	
	3	16000	3490	12	1892	34	34	
	Average	16000	3555	12	2100	38	31	
	SD	0	97	0	191	3		3
MUA	1	16000	2785	10	1942	35	29	
	2	16000	2037	8	1941	35	24	
	3	16000	2660	10	1746	31	31	
	Average	16000	2494	9	1876	34	28	
	SD	0	401	1	113	2		3

Abbreviations

B_{saving}	Mass of fuel savings per stove per session
$B_{y,saving}$	Mass of fuel savings per stove per year
CCT	Controlled cooking test
CDM	Clean Development Mechanism
CO_2e	Carbon dioxide equivalent
C_{pb}	Specific heat capacity of the batter mixture [$\frac{kJ}{kgK}$]
C_{pw}	Specific heat capacity of water [$\frac{kJ}{kgK}$]
$EF_{projected, fossil fuel}$	Emission factor of projected fossil fuel [t CO2e/TJ]
ER_y	Potential yearly emission reduction [t CO_2e]
$f_{NRB,y}$	Fraction of nonrenewable biomass
h_{fg}	Specific heat of vaporization of water [kJ/kg]
ICS	Improved cook stove
IPCC	Intergovernmental Panel on Climate Change
m_{bb}	Mass of batter baked [kg]
m_{ch}	Mass of leftover char [g]
m_{df}	Equivalent mass of dry fuel wood [g]
m_{fc}	Mass of fuel wood consumed [g]
m_{we}	Mass of water evaporated [g]
MC	Moisture content [%]
MUA	Mekelle University prototype with Aluminum pan
MUC	Mekelle University prototype with Clay pan
MUG	Mekelle University prototype with Glass pan
$NCV_{biomass}$	Net calorific value of the fuel wood [TJ/kg]
NCV_{ch}	Net calorific heat value of char [kJ/kg]
NCV_{df}	Net calorific heat value of eucalyptus dry wood [kJ/kg]
P_{saving}	Percentage fuel savings
SD	Standard deviation
Sfc	Specific fuel consumption [g/kg]
SSA	Sub-Saharan Africa
T_b	Water boiling temperature [°C]
T_a	Ambient temperature [°C]
UNFCC	United Nations Framework Convention on Climate Change
u_{saving}	Uncertainty of data in fuel saving [%]
$u_{\eta_{th}}$	Uncertainty of data in thermal efficiency [%]
η_{th}	Thermal efficiency [%]

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Author contributions

AHT and MSA contributed to the conception, design and fund acquisition. AHT, MBK, KT and MHH contributed to data acquisition and analysis. AHT and MBK drafted the manuscript. All authors contributed to the interpretation of data, writing and editing of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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