Article

Evaluating the performance of improved stove for biomass fuel efficiency and carbon emission reduction in Megech Watershed, Ethiopia

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Abstract

In many Sub-Saharan African countries, fuelwood collection is among the most significant driver of forest degradation. There are few studies on improved cookstove emissions and fuel use performance in Ethiopia. Therefore, the objectives of this study were evaluating the specific fuel performance of the improved cookstove and impact of improved cookstove on fuelwood consumption and CO_2 emission in Megech Watershed. For data collection, both experimental and survey designs were employed. For household survey a total of 385 households were selected for interview using multistage sampling and 10 control coking test trials were performed using Mirt stove and traditional three stone open fire for injera baking. The result revealed significant difference ($t = -13.658$; $p = 0.0001$) was seen between ICS (improved cookstove) and three stone open fire on the controlled coking test experiments. The use of Mirt stove under field conditions was saving 35.56% of fuelwood for injera baking in Megech Watershed. Generally, the ICS have dual purpose of saving fuelwood and mitigating forest degradation by saving 10071.04 tons of CO_2 per year. Therefore, Mirt stove are an effective and efficient contribution to securing carbon storage in forests. The contribution of ICS to the reduction of CO_2 emission, forest degradation and household workload can be improved by increasing the capacity of the households to use the ICS. Finally further study should be done particularly stove performance experiment at different seasons.

Keywords aerosols; Mirt stove; carbon; consumption; improve cookstove; fuelwood; biomass energy.

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1 Introduction

In many poor nations in Sub-Saharan Africa, deforestation and forest degradation are the most significant sources of greenhouse gas emissions (Hosonuma et al., 2012; Gizachew and Tolera, 2018). At the same time, fuelwood energy is required to maintain livelihoods in this region (Gurung and Oh, 2013). The main driver of forest degradation in these Sub-Saharan countries is the collection of fuelwood for cooking (Dresen et al., 2014), albeit this phenomenon is difficult to quantify, even with sophisticated tools like remote sensing (Herold et al., 2011). Indoor air pollution created by traditional cooking, on the other hand, is a severe health hazard (Jonson et al., 2013). As a result, measures to reduce fuelwood usage through improved cook stoves have the potential to cut emissions while also reducing climate change, conserving forests and improving human livelihoods (Dresen et al., 2014).

For more than 3 billion people around the world, solid fuel is the primary source of residential energy (Mirza et al., 2008). In Sub-Saharan Africa, biomass fuels are used by more than 80% of total population (Vaccari et al., 2012). Ethiopia is also heavily reliant on biomass energy, with roughly 99% of rural households and 80 percent of urban households using it (Mondal et al., 2018).

Cooking consumes more than 80% of the country's total energy supply in the social, commercial and householdsectors (Mondal et al., 2018). As a result, the entire amount of wood used for cooking (estimated in the millions of tons per year) places enormous strain on natural resources (Dresen et al., 2014). If no action is taken, greenhouse gas emissions from forest degradation for fuelwood in Ethiopia are anticipated to rise from 24 Mt of CO_2 in 2010 to 41 Mt of CO_2 in 2030 (CRGE, 2011). Cooking with biomass isn't a problem in and of itself. It becomes an issue, however, when resources are extracted in an unsustainable manner and energy conversion technologies are dirty and inefficient (Mirza et al., 2008).

Traditional cooking stoves are inefficient and produce a lot of particulate matter (PM) and carbon dioxide (CO_2) (Mamuye et al., 2018; Vicente et al., 2015; Wassie et al., 2021; Sutar, 2022). This results in harmful indoor pollution (Anenberg et al., 2013), which causes a wide range of ailments and disorders in developing countries, including respiratory, cardiovascular, reproductive, and cancer (Saldiva and Miraglia, 2004). In Mexico, Pine and colleagues found that ICSs (improved cooking stoves) lowered PM2.5 by 74% and carbon monoxide (CO) concentrations by 78% (Pine et al., 2011). According to Garca-Frapolli and others, the adoption of ICS has greatly improved women's living conditions by conserving wood and lowering indoor air pollution (Garca-Frapolli et al., 2010; Campbell et al., 2021). According to the ICSs, rocket mud stoves burn 1.6 kg less fuel per day than three-stone stoves in Kenya (Ochieng et al., 2013). In Tanzania, improved cookstove adoption lowered women's workload, cut fuelwood consumption, and created job opportunities for stove makers (Bwenge, 2011). Unlike previous research, the enhanced wood-burning stoves (Plancha) provided no benefits in terms of the fuel utilized in Guatemala's highlands (Granderson et al., 2009). Most Ethiopian homes utilize traditional open fire stoves to bake injera (a pancake like thin bread made of teff and wheat flour which is native to Ethiopia), the country's main staple dish; these stoves are made by arranging three stones (Tadesse, 2020) or other materials in a triangle arrangement around the fire (Adem and Ambie, 2017) 90% of the energy supplied heat is lost to the environment as a result of this process (Beyene and Koch, 2013).

Due to the expansion of agriculture, biomass consumption, and other large-scale investment programs in Ethiopia, forest pressure is particularly high (Nguon and Kulakowski, 2013; Gizachew and Tolera, 2018; Betemariyam et al., 2022). Deforestation in Ethiopia has been progressively expanding at alarming rates over the long term. According to FAO estimates (FAO, 2010), natural forests covered 15.1 million hectares in 1990, but only 12.3 million hectares in 20 years. As a result, Ethiopia has lost 140,000 hectares of natural forest each year, with fuelwood collecting playing a key role in the process (FAO, 2010; Feleke, 2002; Gebreegziabher et al., 2002). According to an Ethiopian study that looked at regrowth, fuelwood harvesting, and fuelwood consumption, the harvest is three times the annual permitted cut on a local scale (Haile, 2009).

To alleviate the pressure on forest resources, energy-efficient biomass stoves should be distributed to the community in Uganda (Jagger and Kittner, 2017) and the forest-dependent community in Bangladesh (Roy et al., 2018). As a result, Ethiopia's government has devised a program to disseminate and promote improved biomass cooking stoves in order to reduce fuelwood use and deforestation (CRGE, 2011). The Mirt (means 'best' in Amharic, and these eco-stoves are used for baking Injera, a pancake like thin bread made of teff and wheat flour which is native to Ethiopia, and is also used to cook and boil food while baking without the use of additional fuel) stove is the most popular right now because of its capacity to reduce fuelwood usage (Beyene and Koch, 2013). In Ethiopia, however, research on the performance of Mirt stoves in terms of fuelwood utilization is sparse (Mamuye et al., 2018). Therefore, this study investigates the effect of improved stoves on biomass energy and carbon emission in Megech Watershed, North West Ethiopia.

2 Materials and Methods

2.1 Study site

The Megech watershed is found in the upper Blue Nile basin of Lake Tana sub-basin. In terms of administrative structure, it is found in Central Gondar Zone. Geographically, Megech watershed is enclosed between 12^o29'07"N 12^o45'00"N latitudes and 37^o22'48"E-37^o37'18"E longitudes (Fig. 1). The area covers a total surface of 784.6 km^2. The northern, eastern and western part of the catchment is characterized by rugged topography with chain of ridges bordering sub-catchments within the area and the southern part is characterized by a gently sloping (some extent flate) surface which is an outlet of Megech river to Lake Tana. The Megech river, which is about 75km long, has a drainage area of about 850 km^2 and an average annual discharge of 11.1 m^3/s (TAHAL, 2010) and also dissected by major tributaries of Megech river such as: Dimaza, Shinta, Keha, Angereb, Gilgel Megech and Wizaba streams.

According to Hurni (1998), the Watershed have a unimodal type of precipitation and its agroecology ranges from Highland (Dega) to midland (Woyna Dega). There is a climatic variability in temporal and spatial cases mainly in precipitation. According to analysis of the climatic data from 1952-2016, the annual rainfall is ranged from 991 mm to 1904 mm, with mean annual range of 1119.4 mm but the temperature is comparatively uniform throughout the year. The annual average daily maximum and minimum temperature at Gondar is 22.1^{o}C and 9.7^{o}C respectively (Yihun Dile, 2009). Based on the rainfall, the climate of the area can be categorized in to two broad seasons; the dry season (winter) which covers the period from October to May and wet season (summer) extends from Jun to September, with slight rainfall during, Autumn and Spring.

The socio-economic characteristics of study watershed are mainly mixed crop and animal production. The land use land cover of the watershed is mainly dominated by cultivated land (73%) and followed by grazing land (14%). The forest and shrubland covers about 10% of the watershed. Eventhough, the source of fuel of all households is biomass (fuelwood from forest, plantation, shrubland, etc.) cow dung and crop residue.

2.2 Household survey

For the household's survey, this study was employed multistage sampling procedure. In the 1st stage, the districts in the watershed were categorized based on agroecology. On the 2nd stage, sample respondents were selected purposively. Although the selection of beneficiary households was not done on a random basis, ICS users probably constitute a representative sample of all targeted households. Traditional stove users were selected randomly in the neighborhood of the selected ICS user households. The sample size was determined using Cochran formula (1977).

$$n = \frac{z^2pq}{e^2} = \frac{1.96^2(0.5*0.5)}{0.05^2} = 385 \quad (1)$$

where n = Sample size; z= confidence level (z = 1.96); p = 0.5, q = 1-p, and e = 0.05 (error term).

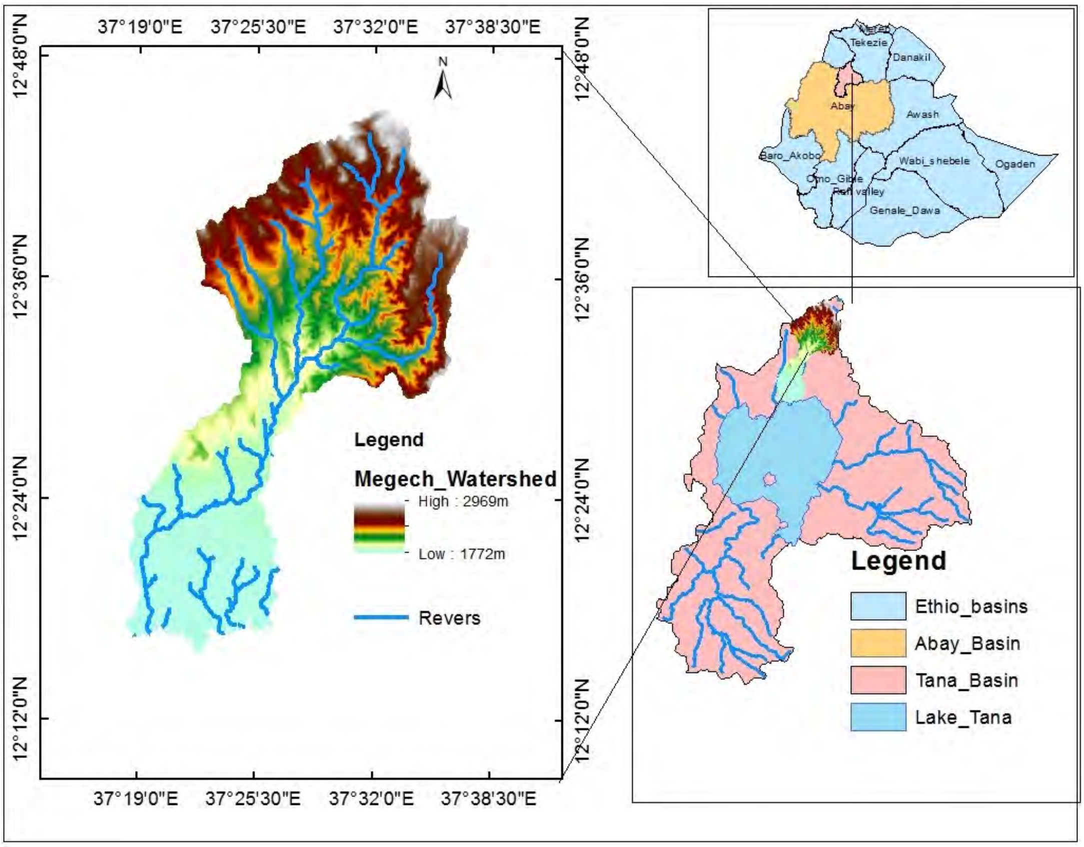

Fig. 1 Location map of the study area.

The questionnaire was developed according to the factors that likely influence fuel consumption and subsequently tested in the field. Most questions were closed-ended. Data collection was carried out by interviews conducted personally by the first author and by a team of DAs (development agents) from selected Kebeles (smallest administrative organ of government in Ethiopia), which is distributed over all Kebeles, guaranteeing a spatial balance of the sampling. DAs conducted the interviews in the Kebeles where they live to ensure maximal confidence between interviewees and interviewers. The questionnaire contained a large list of questions related to fuelwood use, cooking habits and the socioeconomic situation of households. Parameters that were evaluated in this paper are listed in Table 1. The interviews were conducted from February to April 2021.

Table 1 Relevant parameters assessed in the field survey.

Parameter	Unit	Way of Measurement
Household size	Persons	Direct question
Improved stove user	yes/no	Direct question
Type of biomass fuel	Kind	Direct question
Daily fuel consumption without injera baking	kg	Weighted (0.05 kg. accuracy)
Fuel consumption for one injera session	kg wood	Weighted (0.05 kg. accuracy)
Frequency of injera preparation	Times per week	Direct question

2.3 Controlled cooking test

In a small number of randomly selected households (n = 10 which means the number of replications), a performance test of the Mirt stove and traditional three stone stove was conducted, in order to quantitatively determine the efficiency, gain from using the ICS. A controlled cooking test (CCT) (Bailis, 2004) was conducted on both stove types. To minimize the variation in influencing factors, the size of all the improved cookstove must be the same that means 60 cm diameter and height of 24 cm and made by moulds with thickness of 5 mm and for every Mirt stove set up, a three stone open fire was installed using three bricks of same thickness (55.5 cm) and height (23 cm) from the floor as shown in Fig. 2. The same fuelwood was used in all test procedures (*Eucalyptus camaldulensis*; 14%–18% wood moisture). The test followed the standard protocol of the Household Environment and Health (HEH) Project described by Bailis (Bekele et al., 2009; Takahashi and Todo, 2012).

Fig. 2 Types of stoves used in this study *Mirt* (improved) stove (left) and traditional open fire stove (right).

Each household was given the task of preparing enough dough for a regular injera session. The amount of dough and the amount of wood were then weighed. Each injera was timed from the moment it was lit to the time it was removed. The residual wood, charcoal, and ash created by fire were weighed once the injera baking was completed. The specific fuel consumption (SFC) was computed using the wood type/moisture (m), the quantity of dough consumed, and the equivalent dry wood spent, and was expressed in grams of fuelwood consumed per kilogram of dough baked.

$$\text{Specific fuel consumption} = \frac{Dry\ wood\ consumed\ (g)}{dough\ consumed\ (K.g)} * 1000 \qquad (2)$$

2.4 Impacts on carbon balance

The probable impact of fuel savings by using ICS on carbon stocks in the study area was evaluated by estimating total carbon savings achieved by all of the approximately 2,560 improved cook stoves (Mirt stove) disseminated by different NGOs and sold by local enterprises from 2012 up to 2021 (Central Gondar Zone energy sector annual report of 2021), corrected by considering the sources of fuelwood according to the results of the interviews. The fact that only a portion of fuelwood comes from non-sustainable sources was taken into consideration in this way. The calculation was based on IPCC default net calorific values, emission factors and carbon storage in forests (Table 4), according to the formula:

$$E = fuelwood\ saved * fNRB * NCV * EF \quad (3)$$

where E: emissions; NCV: net calorific value (for air dry wood); EF: default emission factor (per unit of energy); fNRB: fraction of non-renewable biomass, has a direct impact on GHGs emission reductions therefore its assessment is of significant importance. The default fNRB value is already approved by the Clean Development Mechanism Executive Board (CDM EB) and accepted by the designated national authority (DNA). Ethiopia default value is 88% (UNFCCC, 2012).

Table 2 Parameters used for calculating carbon emissions.

Parameter	Value	Source
Annual wood savings per stove	2660.97 kg	Table 5
Net calorific value fuelwood (air dried)	15 MJ/kg	(Hall et al., 1994)
Emission factor fuelwood	112 g CO_2/MJ	(IPCC,2006 Volume 2.2)
Conversion CO_2/C	3.667	Ratio molecular weights
Fraction of non-renewable fuelwood (Ethiopian Default value)	88%	(UNFCCC, 2012)

2.5 Time saving analysis

The other important variable is time consumption for preparing food. Therefore, the time saved (TS) using the improved cook stoves was calculated for the experiments of Mirt versus traditional three stone stove was calculated as follows:

$$TS = TCF - TCE \quad (4)$$

where: TCF = time spend cooking with three stone traditional open fire; TCE = time spend cooking with energy saving stoves.

3 Results and Discussion

3.1 Characteristics of the sampled households

Most of the households (76.6%) in the watershed (75.8% of Non-ICS User and 78.6% of ICS User), used fuelwood for all type of food (local bread, injera, Kolo (rosted grain) e.t.c) and beverage preparation (coffee, tea, Tella (well known traditional alcoholic drink in Ethiopia) etc,) as shown in Table 3.

Total (ICS user and non-user) of 18.7% of the households in the watershed used Cattle dung particularly for baking *injera*. The 6.02 and 5.99 were the mean household size for the ICS users and non-ICS users respectively. ICS users have an average injera baking session of 2.4 times per week and non-users bake with an average of 2.42 times per week.

3.2 Evaluating the efficiency of *Mirt* stove

The present study found that the traditional open fire stove (7.506 kg) recorded the highest fuelwood consumption compared to Mirt stove (4.657 kg) per session. In addition, fuel consumption was reduced by 0.15 kg per injera as a result of using Mirt stove (Fig. 3) (Yayeh et al., 2021). The average specific fuel consumption of Mirt stove is 414.18 g of wood per kg of injera. Which implies Mirt stove have total energy savings potential of 35.56%; Which is comparable with the results of Yayeh et al. (2021) with energy savings potential of 31%. But, the present study was lower than Adem and Ambie (2017) and Gulilat (2011) specific fuel consumption experiments that Mirt stove reduce 81% and 48.8% of fuelwood respectively; Similarly, this study was lower than the result of a controlled cooking test conducted by Dresen et al., (2014) where fuelwood savings of 38.9% were found. Therefore, *Mirt* stove is more efficient than the traditional three stone stove.

Table 3 Household Characteristics of respondents stratified by stove type.

Parameters		Total (%) (n=385)	**Non-ICS Users** (%) (n=273)	**ICS Users** (%) (n=112)	p-value*
Fuel used for cooking	Fuelwood	76.6	75.8	78.6	
	Charcoal	4.4	4.3	4.7	
	Cattle dung	18.7	19.6	16.7	0.791
	Crop & tree residues	0.3	0.4	0.0	
Total		100	100	100	
Fuel used for baking	Fuelwood	86.1	84.5	87.6	0.190
	Cow dung	13.9	15.5	12.4	
Total		100	100	100	
		Total Mean (SD)	**Non-ICS user** Mean (SD)	**ICS user** Mean (SD)	p-value[1]
Household Size		6.005 (1.794)	5.99 (1.687)	6.02 (1.783)	0.109
No. of injera session per week		2.41 (0.9)	2.42 (1.08)	2.4 (0.72)	0.102

***According to chi-square, [1] is according to Fisher’s exact test.

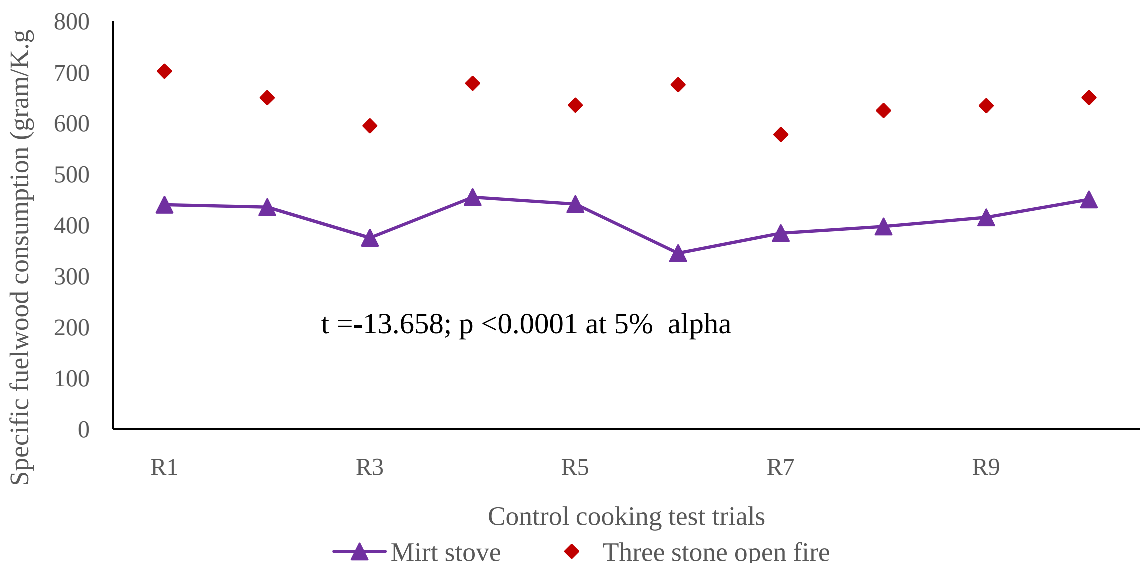

Fig. 3 Specific fuelwood consumption of stoves calculated in gram of fuelwood per kg of dough, where, *Mirt* stove = mean (414.18), SD (36.98) & CV (8.93); Three stone = mean (642.72), SD (37.84) & CV (5.89).

3.3 Impact of improved cookstoves on fuel consumption

The improved (Mirt) stoves consumed less wood fuel than the three stone traditional open fire stoves set up. As revealed in Table 4 *Mirt* stoves consumed a mean of 4.657 Kg of fuel wood (Eucalyptus camaldulensis) per baking session (mean of 30 *injera*). Whereas, the three stone traditional open fire consumed a mean of 7.506 Kg of fuelwood per baking session. The statistical analysis illustrated that there was statistically significant difference (t = 2.551, p = 0.043) between mean consumed fuel wood by Mirt stove and three stone traditional open fire at 95% level of confidence.

Table 4 Experimental result of fuelwood consumption per baking session (kg).

Stove Type	mean	SD	Min	Max	t Stat	p-value (one tail)	p-value (two tail
Mirt	4.657	1.343	3.542	5.43	2.551	0.0217	0.043
Three stone	7.506	1.871	4.47	10.63			
Difference*	2.849						

*Three stone traditional open fire minus*Mirt*stove.

Due to the questionnaire design, the fuelwood was weighed for a whole household, but for comparison reasons with other fuelwood estimations (Dresen et al., 2014; Johnson et al., 2013), the calculation was down-sampled per capita. The average household size was 5.97 (SD = 2.085) and was not significantly different between non-ICS and ICS-users.

In all cooking activities (like preparing local alcoholic and non-alcoholic beverages (coffee, tea, *tella*), sauce preparation, baking local bread and injera), when the use of improved (Mirt) stove, a household saves 2660.97 kg of fuelwood annually with a relative fuel savings of 25.87%.It is possible to say that the improved (Mirt) stove has a great impact on the amount of energy (biomass energy) that the household used for cooking purpose. Different studies like, Sutar (2022), Wassie et al. (2021) and Yayeh et al. (2021) verified that improved cooking stove has a great impact on biomass in particular and forest in general. Improved stove by reducing the amount of biomass burnet.

The present study found that an annual fuelwood consumption of 1708.73 kg/capita (person) for non-ICS users, which is very high consumption compared to the national fuel biomass consumption (TECSULT International Ltd., 2004). This is because of some reasons: (i) the households in the watershed prepare local alcoholic beverage called Tella which consume high amount of energy for preparation; (ii) In the high land area of the watershed the households used fuel (biomass fuel) for heating purpose and (iii) Due to accessibility of the natural forest and bushland, households used fuel in extravagant way. Similarly, fuel consumption in Megech Watershed (North west region) is very high compared to other rural regions in Sub-Saharan Africa countries, such as Uganda and Kenya, where the mean annual consumption of fuelwood was estimated at 542.32 kg/person (Egeru, 2014) and 600.9 kg/person (Ochieng et al., 2013) respectively. This is also confirmed by other studies (Adrianzén, 2013) and can be explained with the inefficiencies in injera baking. Due to the specific cooking characteristics in this region, the transferability to other Sub-Saharan countries is limited.

Table 5 The role of improved cook stove for fuelwood (Energy) saving.

	Non-ICS user (Kg of biomass per capita and year)	**ICS user** (Kg of biomass per capita and year)	Fuel wood savings (Kg)
Baking (injera)*	939.322	582.790	356.531
Cooking (non-injera)**	769.410	683.920	85.490
Total cooking	1708.732	1266.710	442.021
Total annual fuelwood savings per ICS (HHS =6.02)			**2660.97**

*On average, 2.4 injera baking sessions per week. HHS = household size, **savings are a result of cooking on the chimney.

3.4 Improved stove impact on carbon emission reduction

This empirical study illustrated that each ICS (improved cookstove) in usage leads to an average fuelwood savings of 2660.97 kg per year (Table 5). By assuming a net calorific value of 15 MJ/kg (Hall et al., 1994) and an emission factor of 112 g of CO_2 per MJ of fuelwood (IPCC,2006 Volume 2.2) (Table 2), the corresponds result is 4.471 tons of CO_2 per ICS per year. However, the final impact on carbon savings depends on the extent to which fuelwood sources are renewable, (if there will be regrowth of the fuelwood extracted or not). Therefore, we took the fNRB (fraction of non-renewable biomass) for the country Ethiopia default value of 88% (UNFCCC, 2012) and the result become 3.934 ton of CO_2. Therefore, when a household shifts from three stone traditional open fire stove to improved stove, 3.934 ton of CO_2 will notbe emitted to the atmosphere (will be saved) annually. Therefore, the ICS has a great implication for carbon emission reduction.

Carbon savings from the 2560 ICS user households (Central Gondar zone Energy sector annual report of 2021) in the watershed, 10071.04 tons of CO_2 was saved from emitting in to the atmosphere annually (Table 6). In terms of pure carbon, these savings correspond to approximately 2746.40 tons of C (Table 6).

Table 6 The effect of improved stove for carbon emission reduction.

Types of Carbon -savings	Unit
Annual CO_2 savings per stove assuming only non-renewable fuelwood	4.471 tons
Annual CO_2 savings per stove considering regrowth	3.934 tons
Annual CO_2 savings of all 2560 *Mirt* stove	10071.04 tons
Annual C savings of all 2560 *Mirt* stove	2746.40 tons

3.5 The impact of improved stove on the amount of time spent for cooking

The total time taken to bake the required *injera* was evaluated for both *Mirt* and traditional open fire stoves. About 93.9±2.45 and 105.9± 1.87 minutes were the mean time per baking session (average of 30 *injera*) for Mirt stove andtraditional three stone open fire stoves. The time taken for traditional and Mirt stove was comparably similar and there was no significant difference in length of time the stoves taken to bake a given amount of injera ($P > 0.05$). the result of this study were consistent with the result reported by Assefa (2016) and Yayeh et al. (2021).

Table 7 Time taken per baking session (in minutes).

Time taken per /Baking session	mean	SD	Min	Max	t Stat	p-value (one tail)
TSS (Traditional three stone stove)	105.9± 1.87	4.503	102	108	1.953	0.049
ICS (Improved cookstove)	93.9±2.45	11.43	84	103.8		
Difference (TSS-ICS)	12.04					

TSS is Traditional three stone open fire stove and TCS is improved cookstove.

4 Conclusions

Statistically significant difference was seen between ICS and three stone open fire on the controlled coking test experiments of fuel consumption. The use of Mirt stove under field conditions was saving 35.56% of fuelwood for injera baking in Megech Watershed. This seems to be a more realistic figure than the savings often claimed in ICS distribution projects, since efficiency values are usually based on laboratory experiments rather than field-based household studies, possibly leading to overestimates of fuelwood savings. Positive side effects can still increase the total impact of *Mirt* stove on the carbon balance through additional fuel savings for cooking activities using residual heat from the stove chimney. Generally, the ICS have dual purpose on the household and watershed level. On household level, ICS saves fuelwood, reduce smoke and minimized risk of burning. On the watershed level, all of 2560 ICS in the watershed mitigates forest degradation by saving approximately 10071.04 tons of CO_2 per year. Therefore, Mirt stoves are an effective and efficient contribution to securing carbon storage in forests. As a recommendation to practitioners, the contribution of ICS to the reduction of CO_2 emission, forest degradation and household time and workload can be improved by increasing the capacity of the households to use the ICS by providing the ICS through credit and other means and recognizing the importance of women and targeting them in the dissemination activities of ICS. Finally further study should be done particularly the stove performance experiment would be done at different seasons.

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