

Charcoal Production Systems from Smallholder Plantation implications on Carbon Emission and Sustainable Livelihood Benefits in North Western Ethiopia

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Abstract

Charcoal production from *Eucalyptus camaldulensis* small-scale plantations has considerable socioeconomic benefits and improves livelihoods in Ethiopia. Nonetheless, charcoal is produced using traditional earth mound kilns, resulting in poor efficiency, lower charcoal income, and pollution of the environment. This research evaluates the charcoal conversion efficiency, cost-benefit analysis, and emission of gases from improved charcoal-making kilns from *Eucalyptus camaldulensis* small-scale plantations compared to traditional earth mound kilns. A one-way analysis of variance (ANOVA) was performed with a level of significance of t 0.05. The result of the study shows significant ($P < 0.001$) variation in charcoal conversion efficiency among the different tested kilns, with the order of green mad retort kiln (33.7%) > Casamance kiln (32.09%) > MRV steel kiln (28.25%) > traditional earth mound kilns (23.55%). Improved charcoal-making kilns increased the efficiency of wood-to-charcoal conversion by 20–43% compared to the traditional earth mound kilns. The financial profitability analysis revealed that Casamance improved kilns generate the highest equivalent annual charcoal income (117126.9 ETB year⁻¹) followed by Green Mad Retort (82893.8 ETB year⁻¹) and MRV steel kilns (58495.9 ETB year⁻¹) respectively. As was expected, the lowest net present value was found from traditional earth mound kilns (47304.3 ETB year⁻¹). The carbonization time of traditional earth mound kilns was significantly ($P < 0.001$) the longest, with 3.6 times in the Mark V kiln and 2 times in the Casamance kiln. Furthermore, statistical analysis shows that improved charcoal-making technology reduces the emission of carbon dioxide (CO₂) by 36.1–50.7%, carbon monoxide (CO) by 39.2–54.3%, and methane (CH₄) by 29.6–47%. In general, a shift from traditional to cleaner, renewable, and environmentally friendly charcoal kilns is needed.

1. Introduction

Charcoal contribute a significant amount of income, supply energy, and provide multiple socioeconomic benefits to rural households' livelihoods (Ababa, 2019; Andaregie, Worku, & Astatkie, 2020; Bekele & Kemal, 2022; Smith et al., 2019; Tadesse et al., 2019; Thabane, 2020). Charcoal is produced by the combustion of wood under a limited supply of oxygen in a process known as carbonization (Koech et al., 2021). The global charcoal production and consumption trend increased from 17 million tons in 1964 to 53 million tons today, with Sub-Saharan Africa accounts 61 percent of the global charcoal production (Kenne et al., 2022). One-third of the world's population relies on solid biomass for cooking and heating using unsustainable inefficient cook stoves. In Africa alone close to 195 million people or roughly 20 percent of the population in the continent engaged in charcoal production (Dam, 2017). In Kenya, 500,000 people are engaged in charcoal production activities (Njenga et al., 2013). Woodlands in many tropical countries, including Tanzania, and Mozambique, will regenerate within 8–30 years of trees being cut for charcoal (E. Chidumayo & D. Gumbo, 2013; Woollen et al., 2016). Given increased urbanization, population growth, charcoal with little smoke and relatively less costly compared to modern energy sources, the demand for charcoal is expected to double in the coming decade (Doggart & Meshack, 2017; Neuberger, 2015; Raza et al., 2022)

Similarly, in Ethiopia, charcoal production is a primary or secondary livelihood activity that brings immediate cash to millions of households in rural areas. Ethiopia is the third highest charcoal producer in the world after Brazil and Nigeria with an estimated amount of more than 4.4 million tons of charcoal (Dam, 2017). According to the Ethiopian forest action program, fuel wood including charcoal contributes 66% and 62% of the energy consumption in rural and urban areas, respectively (Abebe & Endalkachew, 2011; Endalew et al., 2022). Scientific studies also witness over 300,000 households with at least five family members and over 1.5 million people in Ethiopia depend on the charcoal business (MoWIE, 2010) [1]. Moreover, the per capita consumption of Ethiopian urban households was estimated at 386 kg/head while in rural areas it was merely 9 kg/head (Djampou, 2019). Nonetheless, charcoal has such important economic benefits and even expected to double its demand in developing countries in the coming decades, charcoal producers do not have access to knowledge or improved charcoal-making technology for sustainable charcoal production and use inefficient charcoal making kilns (Baumert et al., 2016; Bekele & Kemal, 2022; Ferede, Alemu, & Mariam, 2019; Koech et al., 2021; Rodrigues & Junior, 2019; Zorrilla-Miras et al., 2018) and there is no incentive or regulation to produce charcoal efficiently in subsharan Africa where food insecurity and poverty is sever (Bekele & Kemal, 2022).

Thus, the production of charcoal using inefficient unsustainable traditional earth mound kilns has poor wood-to-charcoal conversion efficiency with lower charcoal income, higher emission of greenhouse gases, and negative impact on the health of the charcoal producer community. Emissions from traditional charcoal-making were reported 71.2 million tonnes of carbon dioxide and 1.3 million tonnes of methane (E. N. Chidumayo & D. J. Gumbo, 2013) in tropical countries. Africa produces 62% of the 52 million tonnes of charcoal produced globally and one kilogram of unsustainably produced charcoal contributes 6-9kg CO₂ eq along its whole life cycle (Dam, 2017). It was also observed that in 2010 in Ethiopia, 150 MtCO₂e greenhouse gas were emitted. This number is projected to be more than double, 400 MtCO₂e by 2030 under a business-as-usual scenario. Livestock and forest degradation due to cutting and burning fuel wood and charcoal contribute 65 Mt CO₂e, and 55 Mt CO₂e respectively, i.e. 37% of the total emission in the country (Selvakkumaran & Silveira, 2019; M. A. Worku, 2020). Ethiopia sets a target to limit 2030 emissions to 150 Mt CO₂e approximately 250 Mt CO₂e less than in the business-as-usual scenario (Ethiopia, 2019). In this respect, Ethiopia has shown both conservation and policy responses to combat greenhouse gas emissions from agricultural activities. Climate-smart agriculture is mainstreamed into various national policies, strategies, and programs (César & Ekbom, 2013; Yimer, 2016). The aim is to strengthen climate resilience through a more sustainable low-carbon growth pathway with significant emphasis on a sustainable agricultural farming system that is environmentally friendly. Improving the traditional charcoal-making methods through scientific studies will help reduction of deforestation, increase income, and meet objectives of national policy in reduction of greenhouse gases (limit 2030 emissions to 150 Mt CO₂e approximately 250 Mt CO₂e less than in the business-as-usual scenario).

Limited attempts have been made in the past to conversion of fuel wood to charcoal using improved charcoal-making kilns in Africa (Jolien Schure, Pinta, Cerutti, & Kasereka-Muvatsi, 2019), and retort kilns

(Adam, 2009; Jolien Schure et al., 2019) in India. However, there is limited scientific information in the literature that compares different improved charcoal kiln efficiency, financial profitability of kilns and emission of greenhouse gases with conventional practices for producing renewable, cleaner, and sustainable charcoal (Jolien Schure et al., 2019). Previous studies on conversion efficiency evaluation (Charvet et al., 2022; Kammen & Lew, 2005; Ojelel, Otiti, & Mugisha, 2015) failed to consider the amount of the initial wood burn required to fire the carbonization, the unburned wood during the carbonization process, variable moisture contents of dry wood, the diameter of the wood, natural of tree species, and carbonization process which in turn can leads to variable efficiency, economic benefits and emissions of different gases. In addition past studies uses indirect gas emission evaluation instead of directly measuring on-site from charcoal kilns leading to variable emission estimation (E. N. Chidumayo & D. J. Gumbo, 2013; Pennise et al., 2001; Tassie, Misganaw, Addisu, & Tesfaye, 2021) and even the financial profitability of different charcoal-making kilns remain unaddressed. Therefore, comparative evaluation of efficiency and measurement of emission of selected greenhouse gases directly from different types of charcoal-making kilns ranging from improved charcoal-making technology to traditional earth mound kilns for selecting affordable, renewable, and cleaner charcoal production kilns are crucial.

Charcoal production is blamed for looming ecological catastrophe and demanding replacement across the world. Its production in the South Achefer district, Northwest Ethiopia is however different from other charcoal-producing areas. Local smallholder farmers grow *Eucalyptus camaldulensis* tree species cultivated in nurseries, transplanted to fields, and cut at the age of 5–7 years. Eucalyptus tree growers sell the pole and produce charcoal from the residues left (locally called Kirisite) and got considerable income. A study conducted in northwestern Ethiopia showed *Eucalyptus* contributes significant income and other socioeconomic benefits compared to non-tree planter households (Abate, Borges, Marques, & Bushenkov, 2022; Addis, Melak, Tefera, & Kassa, 2016; Mekonnen, Kassa, Lemenh, & Campbell, 2007; Tesfaw, Senbeta, Alemu, & Teferi, 2021). Because of these benefits, smallholder farmers in the study area convert their cropland to *Eucalyptus camaldulensis* small-scale plantation forest (Abate et al., 2022; Molla, Addisie, & Ayele, 2023; Tesfaw, Teferi, Senbeta, & Alemu, 2023). Satellite imagery of vegetation and forest cover changes over 10–20 years analyze shows, a 55% increase in the amount of eucalyptus plantation coverage from 1999 to 2010, and the change expressly climbed to 69% in 2021 compared to the reference period (Tefaw et al., 2023).

Nonetheless, charcoal in the South Achefer district is produced using inefficient traditional earth mound kilns with poor wood-to-charcoal conversion efficiency resulting in lower charcoal income, higher greenhouse gas emissions, and leading charcoal producers to health risks during charcoal making. To the authors' knowledge, there is no scientifically conducted research on improving the traditional charcoal-making technique through different improved charcoal pyrolysis technology in Ethiopia and in the study area as well. Previous studies on *Eucalyptus* were focused on socioeconomic importance (Abate et al., 2022; Gizachew, 2017; Kebede, 2022; Tesfaw et al., 2021), challenges and opportunities (Tefaw et al., 2021), value chain (Nacke, 2021), and its expansion (Molla et al., 2023). With *Eucalyptus camaldulensis* small scale plantation based charcoal production set to remain an important income and energy source throughout the region in the foreseeable future, shifting from the current traditional earth

mound kiln technology to improved charcoal production technologies could be another step required to enhance the efficiency of the charcoal production that can save wood, increases charcoal income, reduce forest deforestation and greenhouse gases emission. Therefore, the current research work was initiated to evaluate, (1) the benefits of different improved charcoal-making kilns technology on wood-to-charcoal conversion efficiency compared to the traditional earth mound kilns, (2) the effects of different improved charcoal-making technology on selected greenhouse emission reduction potential, and (3) to evaluate the carbonization time of different kilns, (4) to investigate cost -benefits analysis of the different kilns and recommend appropriate charcoal making kiln technology in the study area.

[1] Alternative Technologies for Improved Access to Modern Rural Energy Technologies

2. Material and Methods

2.1. Study area description

The study was conducted in the South Achefer district, West Gojam Zone, North Western, Ethiopia located at 11°49' 59.99" North and 37° 09' 60" East (Fig. 1). The study area is about 502 km far from Addis Ababa, the capital city of Ethiopia, and 60 km from Bahir-Dar. It shares borders with North Achefer to the North, Awi Zone to the South and West, and Mecha district to the East. Durbete is its administrative center and it is subdivided into 20 rural and 2 urban Kebele administrations. The district has a 163,052 total population out of which 78,839 are men and 84,213 are women (Dereje, 2019). From this, about 16% of the population is urban dwellers and the rest of 84% are rural dwellers.

Regarding the livelihood activities of the local community in the study area, about 87.9% of the population is engaged in agriculture, 10% are engaged in different merchandise sectors, and 2% are engaged in civil service (Kerebih, 2017). The district has two agro-ecologic conditions; namely, Woynadega (87%) and Kola (13%). The annual temperature of the south Achefer district ranges from 18 °C to 28 °C with annual rainfall ranging between 1365mm – 1623 mm. Agricultural production is characterized by a mixed farming system in which crop production dominates over livestock rearing (Teshome, Dereje, & Asfaw, 2022). Eucalyptus-based small-scale plantation for commercial pole and charcoal production is an important means of livelihood engaging different actors of stakeholders from tree production to charcoal production to end users. The value of charcoal is one of the driver for the expansion of eucalyptus smallholder plantations on agricultural lands (Fig. 2b; (Molla et al., 2023; Tesfaw et al., 2023; A. Worku, Andaregie, & Astatkie, 2021)

2.2. Wood Drying and Wood Diameter Measurement

Moisture content and diameter of the sampled wood are important parameters for the evaluation of wood to the charcoal conversion efficiency of a given charcoal kiln. To do this *Eucalyptus camaldulensis* wood from smallholder plantation land was cut and dried in solar energy for two to three weeks before the carbonization operation begins. This is necessary to reduce the amount of moisture content to minimize

the amount of heat energy wasted during the drying stage. Two moisture readings from 10% of the dry *Eucalyptus camaldulensis* wood were taken using a portable handheld moisture meter with two penetrating probes on each of the selected pieces of wood on the lower, middle, and top of the dry log wood. This reading was repeated on the same pieces of wood to ensure that the moisture content of the dry wood was below 20%. A final dry wood moisture reading was carried out just before arranging the wood for immediate charcoal carbonization. Furthermore, diameter measurement was done using diameter tape as a similar procedure to moisture measurement and all sampled wood has on average a diameter of four centimeters.

2.3. Charcoal production

Charcoal was produced from the same amount of *Eucalyptus camaldulensis* wood by weight base (3502 kg) at Durbete, South Achefer district, North Western, Ethiopia. (Fig. 1). The different charcoal-making production technology used in the current study are traditional earth mounds (Fig. 2a), Casamance (Fig. 2b), Green mad retort kilns (Fig. 2c), and modified Mark V steel (Fig. 2d), with three replications of charcoal production. Traditional earth mound kilns are the sole charcoal-making kiln used by local charcoal producers in North Western, Ethiopia (Bekele & Kemal, 2022; Ferede et al., 2019). The operation of a traditional earth mound kiln starts with wood piling in a conical shape on a well-prepared flat surface with the larger ones put in the middle and covered by teff grass and soil to insulate the carbonizing wood against excessive heat loss before it is ready for carbonization. The Casamance earth kiln in this study is a modified earth mound kiln that is equipped with a chimney, which is fixed on one side (Fig. 2b).

The other improved kiln used in the current study is the modified Mark V kiln which is a Portable steel kiln in the form of a cylinder with a conical top (Fig. 2d). It has outer grooves to be filled with mud on which the second ring and cover fit. The grooves are 5 cm wide and 5 cm deep. To facilitate rolling and reinforce the rings, additional stiffening rings are made from angle iron and welded. The modified Mark V kiln commonly consists of three interlocking parts, namely, the lower ring, the upper, and the conical lid/cover at the top. Whereas, the Green Mad Retort Kiln (GMDR) is a semi-industrial brick retort kiln consists of three parts: (i) an external combustion chamber, where lower-quality wood or other biomass may be used, (ii) a charcoal chamber, and (iii) a chimney that includes a simple system that allows the post-combustion of the gases generated by the carbonization. The construction of those improved charcoal kilns was done by the Ethiopian rural energy development promotion center (EREDPC) funded by UNDP projects with a consultancy of Doctor Getachew Eshete from all the kilns exercised by the operators from the time of firing to the end of carbonization for every kiln.

The completion of wood to charcoal carbonization was observed from the change of the smoke color from the improved kiln chimneys and natural outlets to light blue indicating completion of carbonization. The height of each traditional earth mound, Casamance and Mark V steel kiln piled wood size reduced to about two-thirds of the original size are an indicator of the completion charcoal carbonization. When carbonization was complete, the chimneys and breathers were removed. After the charcoal had cooled down, the soil and unburned little teff straw covering in the case of traditional earth mounds and Casamance kilns were removed using a spade and soil rakes. Unburned wood and no-commercial

charcoal were bagged separately and weighed using balance to determine later in the efficiency calculation of the different kilns used in the study.

2.4. Efficiency and cost-benefit analysis

The effectiveness of the wood-to-charcoal conversion in the kilns is one of the most crucial factors to take into account when choosing to invest in a given charcoal-making kiln. The higher charcoal conversion efficiency from a given charcoal kiln implies higher charcoal sales and income. Following this parameter in mind, the woods to the charcoal conversion efficiency of the kilns were computed with the following formula (Girard, 2002)

$$NE = \left(\frac{Mc}{MDW - MUW + BO} \right) \times 100$$

1

NE = Net efficiency of the kiln, Mc = mass of charcoal, MDW = mass of dry wood, MUW = mass of unburned wood, and BO, is the total energy used to obtain conversion yields (initial burnings).

On the other hand, higher wood-to-charcoal conversion efficiency by itself may not always bring positive income because of the nature of improved charcoal kiln costs, production costs (dry wood, bag, rope, string, teff straw, megaze or blade, cross-cutting wood, harvesting charcoal and producer) and charcoal sale benefits (1 bag = 65 ETB[2] during study season)

To make the comparison easier, all expenses and benefits were considered. Due to the time value of money, future cost and benefit values were discounted to make them easier to compare to current values (Whitman & Terry, 2012). A financial analysis technique (NPV) was adopted to determine different charcoal kiln incentives for making investment decisions. The NPV determines the net returns of the production system by discounting the streams of benefits and costs back to the establishment year using an appropriate discount rate Ethiopian condition (10%) over the lifetime of each kilns. Cost-benefit analysis of improved and traditional charcoal-making technology was computed using the formula (Duguma, 2013; Garrett, Rietveld, & Fisher, 2000; Whitman & Terry, 2012)

$$NPV = \sum_{t=0}^n \left(\frac{(B-C)}{(1+r)^t} \right) \text{—————} (2)$$

Where B = Total benefit generated from the investment, C = Total costs invest for the investment, r = the discount rate, 10% in Ethiopian condition, t = period.

Charcoal-making kiln costs, charcoal income, salvage values, and % of depreciation cost were considered for each life span of the kilns following the reducing balance method. This method is an important mechanism of benefit evaluation of a given new investment because the percentage of the remaining value is reduced and a diminishing amount is charged each (Baldwin, Gellatly, Tanguay, & Patry, 2005)

$$\% \text{ of depreciation} = 100 (1 - \sqrt[n]{R/C}) \text{ ----- (3)}$$

Where, R = residual value; C = initial cost; n = service life

Furthermore, because different charcoal-making kilns have different (useful life span, % of depreciation, and salvage values), we further determined equivalent annual charcoal income for all charcoal-making kilns as follows ;

$$EAE = NPVx \frac{i(1+i)^T}{(1+i)^T - 1}$$

2.5. Measurement of emission of gases from different charcoal production kilns

Selected gas emissions, such as methane (CH₄), carbon dioxide (CO₂), nitrogen monoxide(NO), nitrogen oxides (NO_x), sulfur dioxide(SO₂), and carbon monoxide (CO) from all charcoal production kilns were measured using istagemission gas chromatographic system equipped with a flame ionization detector (FID) and an electron capture detector (Usui et al., 2018). Istagemission gas chromatographic system equipment was zeroed away from the point of greenhouse gas emission before any data measurement was conducted where oxygen gives a value of 20.9–21% and all the other gases and particles read 0%. Once this is completed, the tip of the metallic sampling probe is inserted into a specific vent of each charcoal kiln and the indicated values let to stabilize in five minutes, and the reading is then saved.

2.6. Statistical analysis

The collected data were subjected to statistical analysis using SPSS version 26. A one-way analysis of variance test (ANOVA) was performed with the level of significance set at 0.05. If significant differences between different charcoal-making kilns were found at $p < 0.05$, mean separation was performed using Tukey's HSD tests.

ETB = Ethiopian birrs and using the current currency exchange rate, one Ethiopian birr is equivalent to 0.02 USD.

3. Results and discussion

3.1. Wood to the charcoal conversion efficiency of different charcoal-making kilns

Eucalyptus camaldulensis wood to the charcoal conversion efficiency of the different improved charcoal-making kilns is presented in (Table 1). The result of the study showed production of charcoal using

improved charcoal-making technology kilns significantly ($P < 0.001$) increased the charcoal conversion efficiency and charcoal yield. Significantly, the highest charcoal conversion efficiency was recorded in the order of Green mad retort kiln (33.7%) > Casamance kiln (32.09%) > MRV steel kiln (28.25%) > traditional earth mound kilns (23.55%) (Table 1). The findings revealed that the improved charcoal-making technology with the highest wood-to-charcoal conversion efficiency was found from the Green mad retort kiln while the traditional earth mound kiln had the lowest conversion efficiency. In line with this finding charcoal-making trials in northern Madagascar conducted in the field using Green mad retort (GMDR) external combustion chamber kiln produces an efficiency of about 34% from plantation forests (Michael Temmerman, Andrianirina, & Richter, 2019). Analysis of charcoal yield show improved charcoal-making technology requires a small quantity of wood to produce the same quantity of charcoal as produced in the earth mound kilns. Our findings are comparable with research on the efficiency of charcoal production kiln reported (Adam, 2009; Kammen & Lew, 2005; Kimaryo & Ngereza, 1989; Jolien Schure et al., 2019), higher compared to (Heinze, Vis, Uitdewilligen, & Vos, 2013; Luwaya, Chisale, Yamba, & Malin, 2014; Morgan-Brown & Samweli, 2018; Mutimba & Barasa, 2005; J Schure et al., 2021) and lower than the findings of (Swami, Steiner, Teixeira, & Lehmann, 2009; Wartluft & White, 1984). The likely reason for variable findings with different studies could be the amount of the initial wood burn required to fire the carbonization, the unburned wood during the carbonization process, variable moisture contents of dry wood, the diameter of the wood, nature of tree species, and carbonization process during charcoal making across different location (Charvet et al., 2022; Ferede et al., 2019; Ojelel et al., 2015; M Temmerman, 2016)

Table 1

Mean $\pm$ SE values of charcoal yield and yield components of different charcoal-making technology approaches using *Eucalyptus camaldulensis* at South Achefer district, North Western, Ethiopia.

Kiln type	wood weight	Moisture content (%)	Charcoal yield(kg)	Unburned wood(kg)	Noncommercial charcoal(kg)	Efficiency (%)
Traditional	3502	15.01 $\pm$ 0.06 ^a	685.6 $\pm$ 2.60 ^d	64.40 $\pm$ 1.90 ^c	37.4 $\pm$ 0.83 ^{ab}	23.55 $\pm$ 0.05 ^d
GMDR	3502	15.00 $\pm$ 0.03 ^a	961.8 $\pm$ 3.27 ^a	122.4 $\pm$ 1.73 ^d	19.2 $\pm$ 0.62 ^c	33.70 $\pm$ 0.09 ^a
Casamance	3502	14.97 $\pm$ 0.03 ^a	940.8 $\pm$ 4.21 ^b	46. $\pm$ 0.35 ^b	25.5 $\pm$ 0.50 ^b	32.09 $\pm$ 0.13 ^b
MRV steel	3502	14.95 $\pm$ 0.02 ^a	808.9 $\pm$ 2.02 ^c	173.7 $\pm$ 1.36 ^a	45.3 $\pm$ 5.43 ^a	28.25 $\pm$ 0.25 ^c
P- Value	3502	ns	***	***	**	***
CV (%)		0.44	0.63	2.5	15.1	0.88
Different letters following vertical mean values indicate significant differences at P < 0.05. GMDR: Green mad retort kiln; MRV: Mark v steel kiln; ns: not significant CV: Coefficient of variation; ***: P $\leq$ 0.001						

Green mad retort improved kiln produced on average 961.88 kg (128 .2 bag) of charcoal from 2976 kg of anhydrous wood. With a similar amount of anhydrous wood of 2976 kg, the traditional earth mound charcoal-making kiln at the study site produced the lowest 685.6 kg (97.95 bags) of charcoal compared to the other kilns). Similarly, charcoal yield improvements were also observed from Casamance 940.83 kg (125.4 bags) and MRV-improved steel kilns 808.96 kg (111.5 bags). Studies in this regard state, upgrading the conversion efficiency of traditional charcoal kilns from 15 percent to 25 percent would save 40 percent of wood for the same amount of charcoal produced (Dam, 2017). Higher efficiency from improved charcoal-making kilns could be the radially-arranged stringers wood and the circumferential air space below the apron ensured constant air and gas flows resulting in uniform carbonization. In addition, the chimney at one side of the improved charcoal-making kiln encouraged a very effective reverse, leaving the circumferential air chamber intact throughout the burning period of the charge for continued ventilation (Kimaryo & Ngereza, 1989; Mabonga-Mwisaka, 1983). Traditional earth mound kilns on the other hand proved to be poor and wasteful because too much air circulating in the mound leads to lower charcoal yield (Bekele & Kemal, 2022; Ferede et al., 2019)

The weight of one bag of charcoal varies from 7 kg to 7.5 kg from traditional earth mound kilns and Green mad retort kilns respectively. With a similar bag of loaded charcoal, the variation in weight could be due to temperature difference, the higher the temperature the lower the charcoal yield it gives (Kimaryo & Ngereza, 1989; Meyer, Glaser, & Quicker, 2011). Producing charcoal using improved charcoal-making technology kilns in our finding increased the efficiency of wood-to-charcoal conversion by 20–43% when

compared to the efficiency of traditional earth mound kilns. An analysis of conversion efficiency results from carbonization tests with different types of wood and kilns, including traditional masonry or earth kilns operated in various regions of the world, point to highly variable charcoal yields of typically within 20–35 wt.% (Nahrul Hayawin & Idris, 2022; Jolien Schure et al., 2019; Sparrevik, Adam, Martinsen, & Cornelissen, 2015).

A high yield of conversion efficiency means that smallholders in the south Achefer district of the study area can earn a higher charcoal yield on the same small plots of land from the *Eucalyptus camaldulensis* small-scale plantation-based charcoal production system. Improving the efficiency of the wood-to-charcoal conversion process has also the potential to both spare trees and lower greenhouse gas emissions. Reducing the amount of dry wood needed to produce the same amount of charcoal, more trees and shrubs are left standing, along with their stored carbon thereby mitigating climate change which otherwise have been cut if a traditional earth mound kiln was used (J Schure et al., 2021). Furthermore, the finding of the study implies that improving the wood-to-charcoal conversion efficiency using improved kilns would lead to the expansion or afforestation of *Eucalyptus* plantations on degraded land which has previously never been covered with trees. Indicators of eucalyptus plantation-based charcoal production sustainability are their higher benefit compared to croplands, rotation of eucalyptus plantation every 5–7 years of harvesting, conversion of even fertile land and degraded land to afforestation of eucalyptus plantation for charcoal production (Tesfaw et al., 2023; A. Worku et al., 2021). So improving the wood charcoal conversion efficiency and emission reduction will further increase its sustainability and more expansion to degraded lands.

On the other hand, our finding indicates smallholder charcoal producers in the study area lose about 20–43% of their total charcoal production because of using inefficient traditional earth mound kilns in the South Achefer district, North Western, Ethiopia. Looking into the values of uncommercial charcoal, the GMDR kiln reduces the uncommercial charcoal by about 95% when compared to the earth mound system (Table 2). This is because the carbonization process in the improved kiln is more uniform than the traditional earth mound charcoaling practice. However, the unburned wood percentage increased by 90% in the GMDR compared to the traditional kiln. This could probably be because of poor dry wood arrangement during wood stacking and the design of the kiln, and the inexperience of charcoal producers during full-time carbonization. Training of charcoal producers will lead to the development of several skill sets within the community such as operation and maintenance of improved kilns, and pricing strategy which in turn will lead to increasing kiln efficiency.

Table 2

Mean $\pm$ SE values of selected greenhouse gas emission in kilogram per tonne of charcoal produced from *Eucalyptus camaldulensis* at South Achefer district, North Western, Ethiopia

Kiln type	CO ₂	CO	NO	NO _x	SO ₂	CH ₄
Traditional	2632.77 $\pm$ 22.23 ^a	486.87 $\pm$ 11.97 ^a	1.27 $\pm$ 0.09 ^a	1.80 $\pm$ 0.09 ^a	0.73 $\pm$ 0.03 ^a	52.37 $\pm$ 1.3 ^a
Casamance	1682.37 $\pm$ 11.66 ^b	295.93 $\pm$ 8.13 ^b	0.77 $\pm$ 0.04 ^b	0.73 $\pm$ 0.04 ^b	0.43 $\pm$ 0.04 ^b	36.87 $\pm$ 0.58 ^b
GMDR	1295.87 $\pm$ 13.29 ^d	222.57 $\pm$ 5.26 ^c	0.23 $\pm$ 0.03 ^c	0.37 $\pm$ 0.03 ^c	0.37 $\pm$ 0.03 ^b	27.73 $\pm$ 0.42 ^c
MRV steel	1541.37 $\pm$ 22.75 ^c	265.60 $\pm$ 6.26 ^b	0.17 $\pm$ 0.03 ^c	0.43 $\pm$ 0.03 ^c	0.37 $\pm$ 0.03 ^b	32.13 $\pm$ 0.57 ⁶
P-value	***	***	***	***	***	***
CV	1.7	4.5	13.3	8.1	11.3	3.8
Different letters following vertical mean values indicate significant differences at P < 0.05. GMDR: Green mad retort kiln; MRV: Mark v steal kiln; ns: not significant CV: Coefficient of variation; CO ₂ : carbon dioxide; CO: carbon monoxide; NO: nitrogen monoxide; NO _x : nitrogen dioxide; SO ₂ : Sulphur dioxide; and CH ₄ : methane; ***: P $\leq$ 0.001						

3.2. Greenhouse gas emission in kilogram per tonne of charcoal produced from *Eucalyptus camaldulensis* small-scale plantation

Analysis of greenhouse gas emission data has shown significant variation among the different charcoal-making technology kilns. Significantly, (P < 0.001) lower selected greenhouse gases emission were recorded in the order of GMDR < MRV steel < Casamance < traditional earth mound kilns (Table 2). The lowest kilogram per tonne of charcoal of CO₂ (1295.87) was found at Green mad retort kiln, followed by MRV steel (1541.37), and Casamance (1682.37), while the highest at the traditional earth mound kiln (2632.77). In addition, our findings from one-way analysis of variance show, the emission of carbon mono oxide (CO) and Methane (CH₄) in kg/tonnes of charcoal produced were 222.57 $\pm$ 5.26 and 27.73 $\pm$ 0.42 from Green mad retort, 265.60 $\pm$ 6.26 and 32.13 $\pm$ 0.57 from MRV steel, 295.93 $\pm$ 8.13 and 36.87 $\pm$ 0.58 from Casamnce and 486.87 $\pm$ 11.97 and 52.37 $\pm$ 1.3 from Traditional earth mound kilns respectively. In agreement with this finding, comparable mean emission factors of different gases from improved charcoal-making kilns (kg tonne⁻¹ charcoal) were 1950 $\pm$ 209 for carbon dioxide (CO₂), 157 $\pm$ 64 for carbon monoxide (CO), 24 $\pm$ 17 for methane (CH₄), and compared to the emission of gases from non-retort kilns; CO₂ = 2380 $\pm$ 973, CO = 480 $\pm$ 141, and CH₄ = 54 $\pm$ 29 (Sparrevik, Adam, & Martinsen). Another study from charcoal-making kilns commonly used in Kenya and Brazil shows grams of pollutant per

kilogram of charcoal produced ranged from 543 to 3027 for CO₂, 32–62 for CH₄, 143–373 for CO, 24–124 for total nonmethane organic compounds, 0.011–0.30 for N₂O and 0.0054–0.13 for NO_x (Pennise et al., 2001). Similar trends but very limited emission (less than 0.77 kg/tonnes of charcoal) of gas (NO, NO_x, and SO₂) concentration-time profiles were observed in all types of charcoal kilns used, indicating that the carbonization process unfolds quite uniformly across the kiln cross-section. There were observed some differences in instantaneous concentration values of emission measured across all kilns. For example, an increasing trend in the concentration of carbon monoxide (CO) and methane (CH₄) was seen between days 2 for improved kilns and 2–4 days for traditional earth mounds. This is especially the cases of CO₂ and CO by far the dominant product species in the carbonization gas: these species start to increase as soon as N₂ and O₂ start to plummet in the next four days (Charvet et al., 2022)

Improved charcoal-making technology reduces the emission of gases such as Carbon dioxide (CO₂) by 39.2–50.7%, carbon monoxide (CO) by 39.2–54.3%, and Methane (CH₄) by 29.6–47% respectively. From this study, one can easily understand that improved charcoal-making kilns decrease the quantity of wood used for charcoal production through the improvement of techniques and the utilization of chimneys helps reduce the pollution of the atmosphere by reducing the greenhouse gases emission (Ahmad et al., 2022; Cornelissen et al., 2016; Girard, 2002; Rai, Brown, & Ruwanpura, 2019; Tippayawong, Santiteerakul, Ramingwong, & Tippayawong, 2019). Looking at emission reduction capacity at each kiln shows Green mad retort kiln reduces the highest percentage reduction of Carbon dioxide (CO₂) by 50.7% followed by MRV steel kiln at 41.5% and Casamance at 36.1% respectively. Other studies also indicated GMDR kiln as one of the cleanest charcoal-making technologies with less emission of methane (CH₄) (Schettini et al., 2022; M Temmerman, 2016; Michael Temmerman et al., 2019; Tippayawong et al., 2019). Due to methane burning, the kiln-furnace system has technological advantages over conventional charcoal production systems in addition to being less damaging to the environment (Ribeiro, Carneiro, Lana, & Valverde, 2020).

The environmental impact of carbonization gas such as CO is toxic and therefore has a direct effect on local community human health and the environment in particular and natural resource management in general at large (Rai et al., 2019; M Temmerman, 2016). The lowest greenhouse gas emission from GMDR improved kiln is the kiln returns the smoke gases from the carbonization chamber back to the external fire-box, burns the volatile a higher proportion of the tar components almost completely, and uses the heat for further wood to charcoal carbonization process (Michael Temmerman et al., 2019). Thus, improved charcoal kilns will lead to lower emissions allowing countries in Sub-Saharan Africa to play their role in tackling climate change, whilst benefiting from a renewable source of cooking fuel. The values of greenhouse gas emission particularly methane in the present study is higher compared to the study in Madagascar (Michael Temmerman et al., 2019). This difference in values could be probably the different nature of wood diameter, moisture content, and carbonization process during charcoaling (Kammen & Lew, 2005; Ojelel et al., 2015)

Moreover, a 39.2–54.3% emission reduction of carbon monoxide (CO) from the three improved kilns was observed compared to the traditional earth mound kilns. In agreement with our finding some studies highlighted that the shift from traditional to highly efficient improved charcoaling kilns could reduce carbon monoxide (CO) emissions by up to 70% (Dam, 2017; Ekeh, Fangmeier, & Müller, 2014; Nabukalu & Gieré, 2019). The values of emission of nitrogen monoxide (NO), nitrogen dioxide (NO_x), and Sulphur dioxide (SO₂) are very small in number and insignificant almost across all kilns. Therefore, improved charcoal-making kilns can contribute to fewer emissions by saving wood input and capturing or recycling part of pyrolysis gases (Mwampamba, Owen, & Pigaht, 2013)

3.3 Carbonization time of wood to the charcoal conversion of *Eucalyptus camaldulensis* dry wood of the different improved charcoal-making kilns

The average duration of carbonization by the GMDR and traditional earth mound kilns were significantly the longest (144 hours) while the shortages were 40 hours at MRV and 72 hours at Casamance kiln (Fig. 3). Traditional earth mound kilns produce 685.9 kg of charcoal on average every 6 days, while Casamance and MRV steel kilns produce 940.83 kg and 808.6 kg of charcoal every 3 and 2 days respectively. In the case of the GMDR kiln, the longest 96 hours were taken for colling phases and only it took 48 hours for effective carbonization. In other reports by the Namibian charcoal association, the charcoal carbonization cycle with the traditional kiln was around 144 hours compared to 24 effective carbonization times using the Green mad retort kiln (M Temmerman, 2016). The time of wood to charcoal conversion was reduced to 50 and 72% when charcoal was produced using Casamance and Mark V steel kilns and this value is comparable with the result of (J Schure et al., 2021). In cases of traditional earth mound kilns constant supervision by the charcoal producer is needed until carbonization gets completed. Effective operation is the time during which the kiln ventilation system needs close attention for maximum conversion efficiency. Regulation of air inlets and sealing of cracks and leaks need careful attention.

3.4. Cost-benefit analysis of the different charcoal-making kilns

Improving the traditional ways of charcoal-making techniques with improved kiln technology would increase charcoal income from *eucalyptus camaldulensis* smallholder plantation in the study area in addition to improved efficiency and environmental benefits (Table 1&2, Figs. 3&4). Since the installation costs of improved charcoal kilns are higher than those of traditional kilns, they must generate more charcoal per unit of wood to be more appealing to rural smalholder farmers. The financial profitability of the different charcoal-making kilns presented in (Fig. 5) shows Casamance improved charcoal-making kiln generate significantly the highest equivalent annual charcoal income (117126.9 ETB year⁻¹) followed by Green mad retort (82893.8 ETB year⁻¹) and MRV steel kiln (58495.9 ETB year⁻¹) respectively.

As was expected the lowest net present value was found from traditional earth mound kilns with charcoal income of (47304.3 ETB year⁻¹). Increased energy efficiency would result in more biomass being available for other uses and benefits as a result of an increase in the proportion of rural families with more effective biomass stove presences (Gebreegziabher, Van Kooten, & Van Soest, 2017; Nigussie et al., 2021; Villamor, Guta, & Mirzabaev, 2020). Poor carbonization from traditional earth mound kilns widely used in Africa results in the loss of woody biomass, low revenues for charcoal producers, high pollution levels, and increased greenhouse gas emissions (Mugo, Nungo, Odongo, Chavangi, & Abaru, 2007)

In this section, it was observed that the costs of kilns affect the benefits of charcoal sales from each charcoal production technique regardless of their wood-to-charcoal conversion efficiency. For example, the efficiency from Green Mad retort (37.7%) was higher compared to Casamance (32.09%). But the higher net present values were recorded from Casamance kiln (117126.9 ETB year⁻¹). This could be due to the kiln cost (GMDR = 48333 ETB vs Casamance = 15000 ETB) and the short carbonization time observed at Casamance improved kiln leads to frequent charcoal production per year compared to the other kilns used in our study (Ribeiro et al., 2020; Schettini et al., 2021). Efficiency and annual equivalent income show similar trends for both MRV steel and traditional earth mound kilns. Improved charcoal-making kilns generate charcoal at considerably lower financial and economic costs per unit of wood with higher financial benefits (Schettini et al., 2021; Swami et al., 2009). The study by (Oliveira et al., 2014) revealed for the same amount of charcoal produced, wood consumption was 20% lower with the kiln furnace system than with the "hot tail" type, which improved cash flow and economic outcomes and increased profitability by 16.4%

The study also revealed except for the Casamance improved kiln, MRV steel and Green Mad retort kilns reduced the cost of wood cross-cutting by 50 and 75% respectively. The wood crosscutting cost reduction in the case of the improved kiln was because the wood log is cross-cut about 1-1.5 meters long compared to cross-cutting wood less than 80 cm for traditional earth mound kilns. In addition, the cost of teff straw was reduced by 100% since Green made retort and MRV steel kiln, never use teff straw for covering of the kiln or mound. Moreover, superimposed metal barrels in improved kilns would allow beneficiaries to collect wood vinegar, which can be used to control insect pests and crop diseases. But, Green Mad retort kilns are stationary once built, they can only be used in areas with an easy permanent supply of *Eucalyptus camaldulensis* dry wood in one area where it can works in the study area of South Achefer district. Our finding indicates that Casamance-improved charcoal kilns are mobile and easy to move to other parts of the farmland, charcoal producers can use this form of charcoal-making kilns widely. In the case of stationary or fixed dry wood charcoal production sites, both GMDR and Casamance kilns can be used.

4. Conclusion

It has been used three types of improved charcoal-making technology kilns (Green Mad Retort, Casamance, Mark V portable steel) and traditional earth mound kilns for comparative analysis of their wood-to-charcoal conversion efficiency, greenhouse gas emission and carbonization time in North

Western Ethiopia, particular focus on South Achefer district. The result of the analysis has shown that improved charcoal-making technology kilns increased the efficiency of wood-to-charcoal conversion by 20–43% compared to the traditional earth mound kilns. A high yield of conversion efficiency means that smallholders can earn a higher charcoal yield on the same small plots of land from the *Eucalyptus camaldulensis* small-scale plantation-based charcoal production system. Furthermore, the carbonization time of the traditional earth mound kiln which was widely used in the study area was reduced to 50% and 72% when charcoal was produced using improved kilns. This implies on the other hand within the same time given, charcoal producers in the study area can produce at least one second round of charcoal production or can engage themselves in other livelihood activities while one round in a traditional earth mound kiln. Financial profitability analysis on different charcoal-making kilns shows Casamance and Green mad retort improved kilns are more financially profitable in the study area compared to the traditional earth mound kiln.

Furthermore, improved charcoal-making technology reduces the emission of gases such as carbon dioxide (CO₂) by 36.1–50.7%, carbon monoxide (CO) by 39.2–54.3%, and Methane (CH₄) by 29.6–47% respectively. In general, results obtained from *Eucalyptus camaldulensis* wood *carbonization* strongly support the extension of the Casamance and Green mad retort kiln as the technologies provide better wood charcoal conversion efficiency, net present values and environmental benefits. Thus we recommend the government of Ethiopia shift from traditional charcoal making from *Eucalyptus camaldulensis* small-scale plantations to sustainable and environmentally friendly improved charcoal-making kilns. This can be done through governments and policies should subsidize charcoal producers (a stumpage fee or harvest quota, tax incentives, voluntary certification initiatives) or through voluntary carbon markets, climate funds and increasing charcoal prices has to be considered) when one produces charcoal using improved kilns than traditional earth mound kilns. This will attract local charcoal producers towards renewable and a more sustainable improved charcoal production system.

Declarations

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Data Availability Statement

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

Code availability: Not applicable

Declaration of competing interest

The authors declare that there is no known competing interest

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Author's contributions

ET and SS has made substantial contributions in conception design, acquisition of data, interpretation of results and leading the overall activities of the research. SA engaged in designing and data analysis, has given also the final approval of the version to be published. EB, AA and BB contributed in designing, data collection and analysis of this research. All authors read and approved the final manuscript.

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Figures

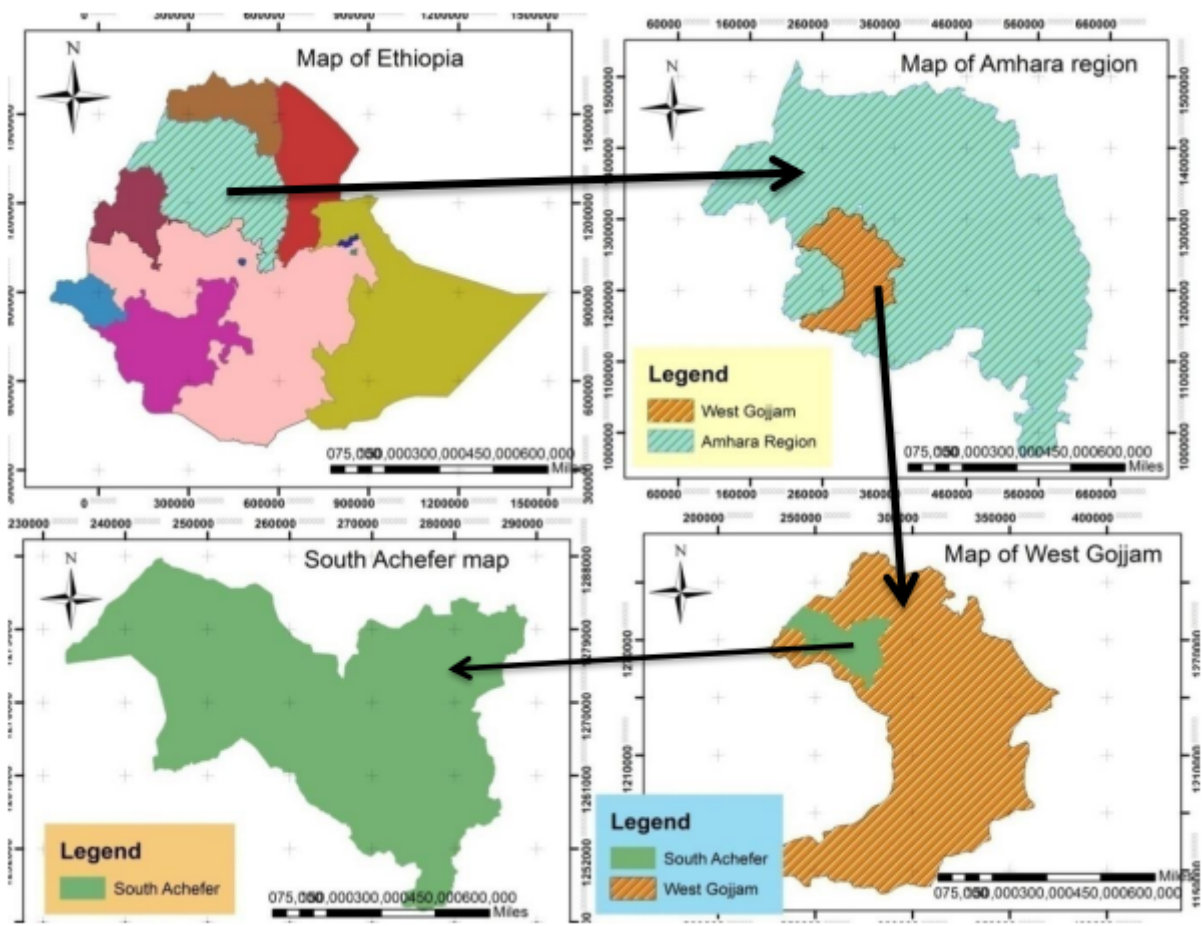


Figure 1

Map of the study area



Figure 2

Existing traditional charcoal production technique on converted agricultural land (a) and around residential areas (b). Photo credit researcher (2022).



Figure 3

The different charcoal production technology used in the current study; earth mound kiln (a); Casamance (b); Green mad retort (c); MRV steel (d). Photo credit researcher (2022).

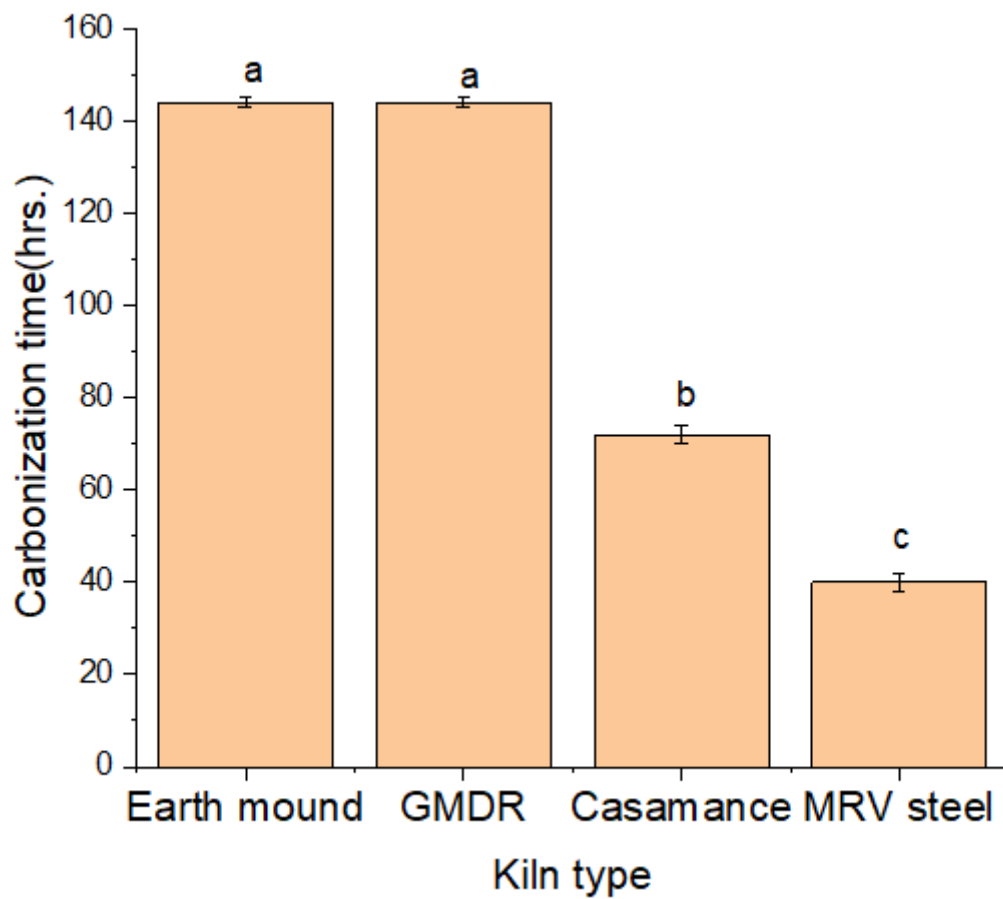


Figure 4

Carbonization time of the different charcoal-making kilns in the South Achefer district, North Western, Ethiopia. Columns with different letters are significantly different at $P < 0.05$. GMDR: Green mad retort kiln, MRV: Mark v kiln; Error bars: mean $\pm$ SE.

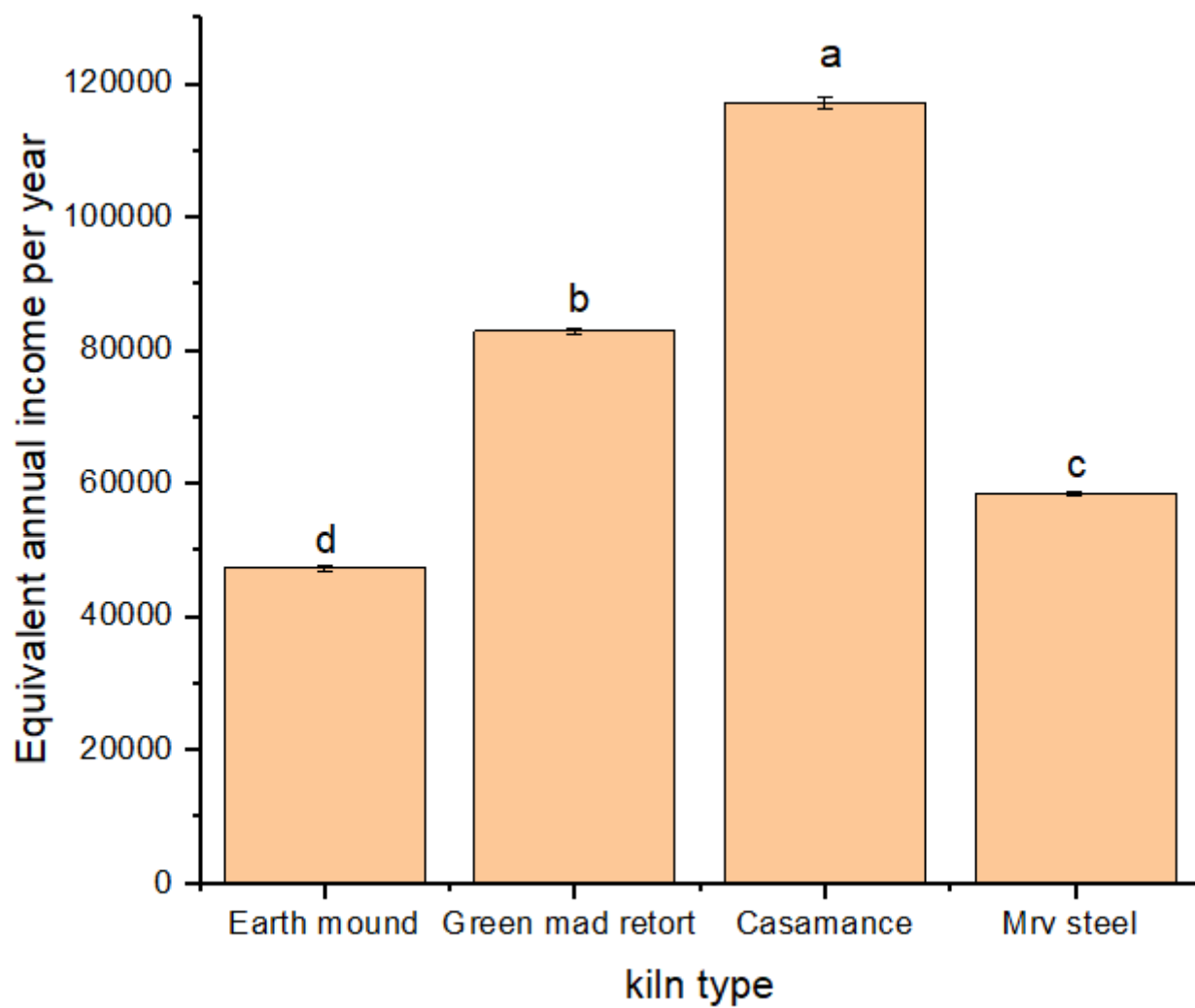


Figure 5

Financial profitability of the different charcoal-making kilns