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Improving traditional charcoal production system for sustainable charcoal income and environmental benefits in highlands of Ethiopia

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ABSTRACT

Charcoal production from Acacia decurrens has shown considerable advantages for enhancing livelihoods and boosting government revenue in Ethiopia. However, the current reliance on unsustainable traditional Earth mound kilns diminishes these benefits, causing reduced charcoal income and notable environmental damage. Therefore, there is a pressing need to improve the traditional charcoal production system. The objectives of this study were evaluating different improved charcoal production approaches on charcoal conversion efficiency, financial profitability, and gas emission reduction potential compared to traditional charcoal making in the Fagta lokoma district, Ethiopia. Charcoal was produced from Acacia decurrens small-scale plantation, using improved kilns (Green mad retort, MRV portable steel, Casamance) and traditional Earth mound kilns, with three replications of production. Statistical analysis revealed a significant increase in charcoal conversion efficiency (at $P \leq 0.001$), with the MRV steel kiln exhibiting the highest efficiency (41.57%), followed by the Green mad retort (36.14%) and Casamance (34.07%). Conversely, the traditional Earth mound kilns displayed the lowest conversion efficiency (24%). The findings demonstrated that improved charcoal-making kilns enhanced wood-to-charcoal conversion efficiency by 41–72% compared to traditional kilns. Moreover, the study reveals a significant increase in average charcoal income per hectare (at $P \leq 0.001$), with higher earnings (284,824.4 ETB) at MRV steel kiln, and lower-income (71,580 ETB) at traditional Earth mound kilns. Improved charcoal-making kilns significantly ($P \leq 0.001$) reduced harmful gas emissions compared to the traditional Earth mound method. Reduction percentages were substantial for various gases: CO_2 (46–57.9%), CO (29.4–56.6%), NO (61.7–86.1%), NO_x (56.6–86.2%), SO_2 (41–62.8%), and CH_4 (35.7–57%). In coclusion, the improved kiln technology has substantially enhanced the efficiency of charcoal conversion, resulting in beneficial effects through emissions reduction. To champion sustainability and cultivate positive socio-economic outcomes, it is imperative to extensively adopt these eco-friendly kilns in areas where charcoal production is prominent.

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1. Introduction

Charcoal is an essential renewable energy source, obtained through biomass carbonization in an oxygen-limited environment [1]. It plays a crucial role in low-income countries, offering significant income and various socioeconomic benefits, particularly in areas where access to modern energy sources is limited [2–5]. Globally, 53.2 million tons of charcoal are produced, with Africa contributing around 63% [6]. Charcoal is the primary cooking fuel for 1.3 billion people worldwide and 195 million people in sub-Saharan Africa [7,8]. Wood charcoal plays a vital role in reducing rural-urban migration in Zambia and employing 500,000 individuals in Kenya [9]. Its widespread use is due to its affordability, durability, popularity, and cost-effectiveness compared to alternatives like kerosene and liquefied petroleum gas [10]. The demand and production of wood charcoal in Sub-Saharan African countries are projected to double by 2030, with over 700 million Africans relying on it as a source of income and energy [7,10].

Similarly, in Ethiopia, charcoal and fuel wood play a dominant role in energy consumption, constituting approximately 90% of the total energy used [11]. Ethiopia ranks as the world's third-largest charcoal producer, with production surpassing 4.4 million tons, following Brazil and Nigeria [6]. Due to limited access to electricity and natural gas, many Ethiopian communities heavily rely on fuel wood and charcoal. Charcoal is extensively used for cooking in households, bakeries, restaurants, and small-scale industries [5]. The charcoal business provides income to around 1.5 million people from over 300,000 households [12]. Eight percent of total households and thirty percent of urban households utilize charcoal for daily cooking [13].

Despite the increasing charcoal production and demand in developing countries, including Ethiopia, there is still a prevalent reliance on inefficient and unsustainable traditional kilns. Traditional charcoal production methods are often inefficient, with low conversion rates of wood to charcoal [6,14–16]. This means more trees need to be cut down to produce large amounts of charcoal, which further worsens deforestation. Traditional charcoal production is associated with narratives of environmental degradation, deforestation, and climate change [17,18]. Furthermore, those traditional charcoal production sites are usually not managed sustainably, leading to soil degradation [14].

Traditional charcoal production also involves incomplete combustion, resulting in the release of large amounts of carbon dioxide and other greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O) [19–21]. These emissions are significant contributors to global warming and climate change. In tropical countries, it is estimated that traditional charcoal production emits around 71.2 million tonnes of carbon dioxide and 1.3 million tonnes of methane and this is equivalent to 7% of tropical deforestation [18]. Similarly, greenhouse gas emissions from agricultural activities, including charcoal production, amounted to 150 Mt CO_2e reported in Ethiopia [22]. If current practices persist, this emission level is expected to double to 400 Mt CO_2e by 2030 [22,23]. In the Mecha district of the West Gojam Zone, the traditional production of *Eucalyptus camaldulensis* charcoal results in the release of approximately 24,411.02 tons of CO_2e greenhouse gases [19].

To tackle these challenges, studies emphasizing the necessity of implementing improved modern pyrolysis technology kilns for charcoal production. These advancements can pave the way for sustainable charcoal production, resulting in reduced deforestation and environmental pollution [1]. Moreover, it aligns with climate-smart agriculture initiatives, facilitating the promotion of cleaner and more renewable energy development. Previous studies [20,24,25] have reported that using improved charcoal-making kilns enhances charcoal production. However, these studies overlook important factors such as unburned wood, moisture content of the wood, wood diameter, tree species, and carbonization process for wood-to-charcoal conversion efficiency evaluation. Furthermore, previous studies evaluated greenhouse gas emissions indirectly, utilizing the Intergovernmental Panel on Climate Change formula (IPCC), rather than directly measuring emissions from charcoal kilns [19,20]. This leads to variable findings in terms of charcoal yield, socioeconomic benefits, and gas emissions. The study endeavors to bridge these gaps by considering relevant parameters, enhancing kiln carbonization for improved efficiency and profitability, and conducting emissions assessments with utmost importance. This will aid in identifying cost-effective and efficient charcoal-making technologies that harmonize with local practices, fostering sustainable, renewable, and environmentally friendly charcoal production.

In the Fagta Lokoma district, Northwestern Ethiopia, charcoal production from *Acacia decurrens* small-scale plantation forests is a recent phenomenon [14,26–28]. *Acacia decurrens,* commonly known as green wattle or early black wattle, is a species of *Acacia* tree native to southeastern Australia [29,30]. It is a member of the Fabaceae family and falls under the subgenus Phyllodineae. It is a medium to large-sized tree, usually reaching heights of 5–10 m and sometimes even taller under favorable conditions, and suited to charcoal production. *Acacia decurrens,* are elegantly upright trees, typically reaching heights of 5–10 m but occasionally attaining 20–22 m in favorable conditions [31]. They commonly have single, straight to almost straight main stems with strong, shallow lateral roots [32].

Acacia decurrens were introduced to Northwestern Ethiopia in the early 1990s for short-rotation forestry, to alleviate urban firewood shortages caused by deforestation [33,34]. Consequently, the practice has rapidly expanded, leading to competition for annual cropping and grazing land. Smallholder farmers nurture *Acacia decurrens* seedlings in nurseries, transplant them to fields, and harvest them after 4–6 years, primarily for traditional charcoal production using rotation [3,5,26,35]. This approach has resulted in a significant increase in forest cover, reaching over 50% of the district's total land [26], providing various benefits such as thriving regional charcoal markets, increased income, job opportunities, reduced run-off from degraded lands, and improved acidic soil fertility [2,4,27,36]. Additionally, smallholder farmers adopt intercropping methods during the first year of small-scale plantation establishment, cultivating food crops alongside *Acacia decurrens* trees, and collecting grass the following year [3,26].

All *Acacia decurrens* species are utilized for charcoal production, leaving the foliage and some thin twigs on the ground for fencing and firewood. Charcoal making (charring) is performed on the same land where the plantation was established or on nearby farms, using a series of heaps [26]. Unlike eucalyptus, *Acacia decurrens* do not regenerate from coppice after harvest, and its bare root system allows for easy plowing of the land by farmers [37].

Despite the various benefits of charcoal production from *Acacia decurrens* in the Fagta Lokoma district, the use of traditional Earth mound kilns hinders the efficient conversion of wood to charcoal. This has resulted in reduced income for the communities, health problems, and environmental pollution due to greenhouse gas emissions [14,37]. Therefore, it is imperative to improve the traditional charcoal-making technique by evaluating different renewable and cleaner methods. Previous studies have explored various aspects of *Acacia decurrens* small-scale charcoal production, including its livelihoods contribution [2,26,37], fiber morphology [38], value chains [23], sustainable charcoal production determinants [14], and soil remediation via *Acacia decurrens* [35]. However, to the best of author's knowledge, no previous studies have explored enhancing the traditional charcoal-making technique through modern improved charcoal-making technology in Ethiopia and the study area.

The current study was therefore initiated to evaluate different improved charcoal-making approaches for renewable and cleaner energy in the study area compared to the traditional kilns. Specifically aims to (i) assess the wood-to-charcoal conversion efficiency of various improved charcoal-making technologies, (ii) evaluate the potential reduction of greenhouse gas emissions, and (iii) analyze the benefit-cost-effectiveness of these improved kilns compared to traditional Earth mound kilns. The study could highlight to identify and recommend the most suitable improved kilns that ensure the best economic profitability and demonstrate a high level of environmental friendliness as viable alternatives to traditional kilns. Embracing these technologies will advance both environmental concerns and economic development, bringing our country toward a greener and more sustainable future.

2. Material and methods

2.1. Study area description

The study was conducted in the Fagta Lokoma district, which is situated in the Awi Zone of Northwestern Ethiopia. This district is geographically positioned between 11° 0′ 0″ to 11° 12′ 0″ N Latitude and 36° 42′ 0″ to 37° 6′ 0″ E Longitude (Fig. 1). It spans an altitude range of 1887–2902 m above sea level and encompasses a total area of 65,579 ha [28].

The climate in this area is characterized by a mean annual temperature of 17 °C and a mean annual rainfall of 1629.77 mm, with an extended summer season. The majority of rural households in the study district practice mixed subsistence agricultural farming systems. The main crops cultivated by these households include tef (Eragrostis tef Zucc.), barley (Hordeum vulgare L.), wheat (*Triticum aestivum* L.), and potato (Solanum tuberosum L.) [27].

In terms of land use, the majority of the study area is occupied by croplands, while forested areas are primarily covered by small-scale plantations of *Acacia decurrens* [28]. This *Acacia decurrens* plantations are extensively utilized for traditional charcoal production, mainly catering to local traders at the farm gate. The cultivation of this species involves nurturing seedlings during the dry season

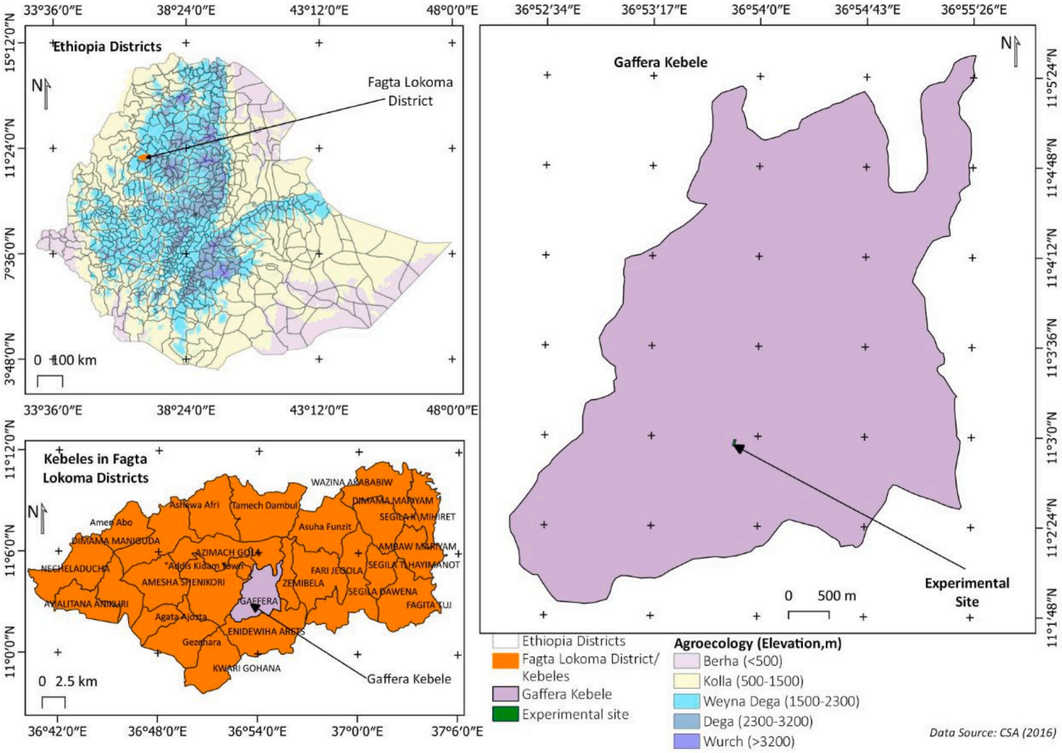

Fig. 1. Map of the study area.

(January–May) and transplanting them during the rainy season (June–August) to ensure sufficient moisture for successful establishment [3]. Interestingly, the area dedicated to *Acacia decurrens* for charcoal production in recent years has surpassed that of any other land use type in the study area [39].

2.2. Wood moisture and diameter measurement

The measurement of wood diameter is important because larger wood diameters may necessitate more energy and time for carbonization, thereby affecting the overall energy efficiency of the charcoal conversion process. Additionally, wood diameter influences heat distribution during carbonization, and larger pieces can result in uneven heat distribution, leading to incomplete carbonization and uneven charring. To ensure accurate evaluations, we sourced *Acacia decurrens* wood from smallholder plantation land. Before commencing the carbonization process, the wood underwent solar drying for a period of two to three weeks (Fig. 2a). The purpose of this step is to minimize the wastage of heat energy during the initial carbonization stage. The wood's diameter was then assessed using a diameter tape, employing a procedure of measuring the diameter of logs at different sections (Fig. 2b). The approach involves wrapping the diameter tape around the wood at lower, middle, and upper log sections, and then taking the average of these three readings to obtain a precise measurement of its diameter. By using this technique, researchers can precisely assess the size of the wood samples, which is essential for understanding their influence on various aspects of the charcoal conversion process. The study revealed that all sampled wood had an average diameter of 6 cm, which was consistent across all types of kilns (Fig. 2b).

Regular moisture content analysis and monitoring during the charcoal conversion evaluation are also essential to ensure consistent and efficient charcoal production. Moisture content can be measured using various methods, such as oven-drying or specialized moisture meters. By controlling and maintaining the appropriate moisture level, one can improve the yield of the resulting charcoal. To determine the moisture content, a portable handheld moisture meter equipped with two penetrating probes was employed, following the methodology outlined by Ref. [40]. From the dry wood, representing 10% of the total *Acacia decurrens* plantations, three moisture readings were taken from different sections (low, middle, and upper). To ensure consistency, these readings were repeated on the same pieces of dry wood, ensuring that the moisture content remained below 20%. Finally, a final average moisture reading was obtained just before arranging the wood for immediate charcoal carbonization (Fig. 2c). Once the moisture content value is obtained, it is subtracted from the wood weight to determine the dry weight of the wood. This step is crucial because moisture is not converted into charcoal; rather, it is released as vapor during the carbonization process. By subtracting the moisture-influenced weight, we obtain the precise dry weight of the wood, which is essential for accurate charcoal conversion evaluations [41]. Subsequently, the wood was cross-cut, weighed, and stacked in preparation for the carbonization process.

2.3. Charcoal production

In this study, a comprehensive evaluation of four charcoal-making technologies was conducted, encompassing a range of kiln types, from mobile to stationary and traditional to retort-based systems. To facilitate comparative analysis, an equal amount of *Acacia decurrens* wood, weighing 2750 kg, was used as the raw material for charcoal production.

The present study employed various charcoal production technologies, namely traditional Earth mounds (Fig. 3a), Casamance (Fig. 3b), modified MRV steel (Fig. 3c), and Green mad retort kiln (Fig. 3d), each replicated three times for charcoal production. Among these technologies, local charcoal producers in the study area exclusively use traditional earth mound kilns. The operation of the Earth mound kiln involves arranging wood in a conical shape on a well-prepared flat surface, with larger pieces of cross-cut wood positioned in the middle. To insulate the carbonizing wood against excessive heat loss, it is covered with teff straw and soil until it is ready for carbonization.

The Casamance earth kiln utilized in this study has undergone modifications, transforming it into an improved earth mound kiln with a fixed chimney on one side. To promote effective air circulation and optimize heat transfer within the kiln, two long poles called stringers have been incorporated. These stringers play a crucial role in ensuring a steady flow of air and facilitating efficient heat distribution. The clamp logs are then stacked in a crosswise manner on these stringers, further contributing to the kiln's enhanced performance.

Fig. 2. *Acacia decurrens* wood drying (a), diameter measurement (b), and moisture measurement for charcoal production (c). *Photo credit researcher, (2022).*

Fig. 3. The different charcoal production technology used in the study: Earth mound kiln (a), Casamance (b), MRV steel (c). Green mad retort (d). *Photo credit researcher, (2022)*.

Another improved charcoal-making technology employed in this research is the modified Mark V kiln. This portable steel kiln takes the shape of a cylinder with a conical top. The kiln is designed with outer grooves, each 5 cm wide and 5 cm deep, which can be filled with sand to secure the second ring and cover. For additional support and reinforcement, angle iron stiffening rings are crafted and welded to facilitate the rolling and strengthening of the rings. The modified Mark V kiln typically consists of three interlocking parts: the lower ring, the upper ring, and the conical lid/cover at the top.

A semi-industrial brick retort kiln known as the Green Mad Retort Kiln (GMDR) is also studied. It is fixed in structure and constructed with brick and reinforced concrete. The GMDR comprises three main components: an external combustion chamber that allows the use of lower-quality wood or biomass, a charcoal chamber, and a chimney with a simple system for post-combustion of the gases generated during carbonization. The construction of these kilns was carried out by the Ethiopian Rural Energy Development Promotion Center (EREDPC) for this study and is the first of its kind in Ethiopia. Given the absence of available improved kilns in our country, this work stands as a pioneering effort and holds the distinction of being the first initiative of its kind.

The process of wood carbonization into charcoal was observed by monitoring the change in smoke color from the kiln chimneys and natural outlets. The color transitioned to light blue, indicating the completion of carbonization [42]. The height of the wood piles in the traditional earth mounds, Casamance, and Mark V steel kilns decreased to about two-thirds of their original size, serving as a clear indicator of the charcoal carbonization's completion [43]. The carbonization duration for each kiln was recorded, starting from the initial burning until the completion of carbonization. To ensure a fair comparison, the carbonization process was initiated simultaneously for all the kilns.

Once the carbonization process reached its endpoint, the chimneys, and breathers were removed. After allowing the charcoal to cool down, any remaining soil and unburned teff straw covering (in the case of traditional Earth mounds and Casamance kilns) were carefully cleared using spades and soil rakes. To assess the efficiency of the different kilns used in the study, the unburned wood and non-commercial charcoal were collected separately, weighed using a balance, and recorded for later calculations.

2.4. *Wood to charcoal conversion efficiency analysis*

The wood-to-charcoal conversion efficiency of the kilns was calculated using (Eq. (1)) following the method described by Ref. [41]. This method holds significant importance as it takes into account crucial factors such as the moisture content of the wood, unburned wood, and the total energy utilized to achieve conversion yields (Eq. (1)). Many studies often overlook these aspects, making this study particularly valuable in providing a comprehensive and accurate assessment of the charcoal conversion process.

$$\mathrm{NE} = \left(\frac{\mathrm{M_c}}{\mathrm{MDW} - \mathrm{MUW} + \mathrm{BO}}\right)\mathrm{x}100\% \tag{1}$$

where, 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).

2.5. *Cost-benefit analysis of the different charcoal-making kilns*

Higher wood-to-charcoal conversion efficiency alone may not guarantee positive income due to the associated costs of improved charcoal kilns and production. To compare the financial benefits of different improved charcoal-making kilns with traditional Earth mound kilns, a cost-benefit analysis (CBA) was employed in this study. It considered various costs, such as *Acacia decurrens*, tree purchasing, labor expenses (including tree cutting, debranching, crosscutting, wood stacking, harvesting charcoal, charcoal producer including charcoal keeping cost, digging, loading, and string), cost for teff straw for covering the pile, sack, rope, saw, charcoal making kiln costs, and revenue from charcoal sales from each kiln (1 sack = 65 ETB [1]during the study season) and 1 sack weights on average

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

7–7.5 kg. The benefits and costs were also translated into the hectare and district levels to evaluate the advantages of each kiln on a larger scale, enabling further recommendations and the selection of appropriate charcoal-making kilns in the study area. Furthermore, the royalty fee was determined by computing 13% of the tax (as set by the government) from the total charcoal sales generated by each kiln. This assessment allows us to make informed decisions regarding the most suitable kiln types for charcoal production in the region.

To facilitate comparison with current values, future cost, and benefit values were discounted considering the time value of money using (Eq. (2)) [44]. The financial analysis technique used was Net Present Value (NPV), which determined the net returns of the production system by discounting benefits and costs back to the establishment year using an appropriate discount rate for the Ethiopian condition (10%) over the lifetime of each kiln. The cost-benefit analysis of the different charcoal-making kilns was computed following the formula proposed by Ref. [44].

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

where B = total benefit generated from the investment, C = total cost invested for the investment, r = discount rate, 10% in Ethiopian condition, t = period.

The evaluation of charcoal-making kiln costs, charcoal income, salvage values, and depreciation costs as a percentage was conducted for each kiln's lifespan, employing the reducing balance method (Eq. (3)). This method is of significant importance as it serves as a critical mechanism for assessing the benefits of new investment [45].

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

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

Moreover, considering that various charcoal-making kilns possess distinct useful lifespans, percentages of depreciation, and salvage values, we proceeded to determine the equivalent annual charcoal income for all these charcoal making kilns using (Eq. (4)) for the purpose of comparison analysis [44].

$$\mathrm{EAE} = NPV\ x\ \frac{i(1 + i)\hat{T}}{(1 + i)^{T} - 1} \tag{4}$$

where, EAE = equivalent annual income, NPV, net present value, i = interests rate, and T = lifespan.

2.6. *Measurement of emission of gases from different charcoal production kilns*

The emissions of various gases, namely methane (CH_4), carbon dioxide (CO_2), nitrogen monoxide (NO), nitrogen oxide (NO_x), sulphur dioxide (SO_2), and carbon monoxide (CO) from each charcoal kiln were measured using the Istagemission gas chromatographic system equipped with a flame ionization detector (FID) and an electron capture detector following the method [21].

Before conducting any data measurement, the Istagemission gas chromatographic system equipment was calibrated at a location away from the greenhouse gas emission point. During the calibration process, the oxygen level was set to a value ranging from 20.9% to 21%, and all other gases and particles were set to register a reading of 0% [21]. Once the calibration was completed, the metallic sampling probe's tip was inserted into a designated vent of each charcoal kiln. The system allowed the indicated values to stabilize for 5 min, and subsequently, the readings were saved for further analysis. The emissions of selected gases were subsequently calculated by dividing the measured emissions from each kiln by the amount of charcoal produced in each respective kiln. To assess the emissions of selected gases on a larger scale, at the hectare and district level, we calculate the total pile per hectare and the overall charcoal production during the study season at the district level. Furthermore, we take into account the total hectare area dedicated to charcoal production throughout the study seasons.

2.7. *Statistical analysis*

The data collected on charcoal yield, yield components, carbonization time, and greenhouse gas emissions underwent statistical analysis using SPSS version 26. To evaluate the significance of the differences, a one-way analysis of variance test (ANOVA) was performed with a significance level of 0.05. In cases where significant differences were found at $p < 0.05$, further analysis was conducted using Tukey's HSD tests to separate the means.

3. Results and discussion

3.1. *Wood to the charcoal conversion efficiency*

The mean values for wood-to-charcoal conversion efficiency of different charcoal-making kilns are presented in Table 1. The sampled wood used in this study had similar moisture content, as it was sourced from smallholder plantations with consistent management practices for *Acacia decurrens*. The statistical analysis revealed significantly ($P \leq 0.001$) higher charcoal conversion efficiency at the MRV steel kiln (41.57%), followed by the Green mad retort (36.14%) and Casamance (34.07%) kilns. In contrast, the traditional

Earth mound kilns, the only charcoal-making technique used by the local communities in the study area, exhibited the lowest conversion efficiency of 24%. Moreover, our study showed that using improved kilns increased the wood-to-charcoal conversion efficiency by 41–72% compared to traditional earth mound kilns. The results demonstrate that using modern and improved kilns can lead to a substantial increase in conversion efficiency compared to the traditional Earth mound kilns. This knowledge can have practical implications for smallholder plantations and local communities, as it highlights the potential benefits of upgrading to more efficient kilns. Increased efficiency means less waste of wood resources, higher charcoal production, and potentially improved livelihoods for those involved in the charcoal-making industry. This finding suggests that adopting improved kilns could be beneficial for charcoal producers and local communities in terms of resource utilization and charcoal production. This can make charcoal production a lucrative activity and provide users with an incentive to engage in sustainable practices. On the other hand, charcoal production using Earth mound kilns is inefficient and unsustainable, leading to poor charcoal conversion efficiency [6,14,16,37,46,47]. Moreover, the improvement in wood-to-charcoal conversion efficiency implies reduced pressure on natural forests, as smallholder charcoal producers can meet their charcoal demand through increased benefits and income from charcoal.

These findings are consistent with other studies conducted in the field, where various research efforts have emphasized the importance of improving kiln efficiency to reduce energy consumption, minimize environmental impact, and enhance overall productivity [48–50]. Previous research on the efficiency of improved charcoal production systems in India and East Africa reported efficiency levels of 30%–42% [51]. Similar results were observed in northern Madagascar plantation forests [52], with an efficiency of 34%, and in Kenya with efficiencies ranging from 27% to 35% [53]. Additionally, a study conducted in Kenya [54] demonstrated an increase in efficiency from 10% to 40.85% by using metallic clay-insulated kilns instead of traditional earth mound kilns. Similarly, in Baringo, improved kilns led to charcoal yield improvements of up to 49% [47]. In contrast to previous studies, our research reveals a higher efficiency in our charcoal kiln compared to improved basic Earth-mound kilns (IBEK) reported in Nigeria [55], but a lower efficiency compared to bamboo and coconut shell charcoal kilns in Thailand, which reported efficiencies ranging from 38% to 45% [56]. These variations in conversion efficiency can be attributed to several factors, including the moisture content of the wood, wood diameter, tree species, and the specific carbonization process employed [43,57].

Improved kilns exhibit higher wood-to-charcoal conversion efficiency due to various factors. Firstly, their enhanced insulation retains heat more efficiently, leading to higher temperatures within the kiln and facilitating a more rapid and complete conversion of wood into charcoal [42,58]. Secondly, these kilns have better airflow management, preventing excessive combustion and ensuring a more efficient conversion process [20,52]. Thirdly, their design focuses on minimizing heat loss, enabling a higher proportion of generated heat to be utilized for charcoal production [58]. Moreover, improved kilns maintain a consistent temperature distribution, promoting uniform conditions for all wood pieces and resulting in higher conversion rates [59]. Additionally, improved kilns often capture and use combustible gases released during the process, further enhancing efficiency [52]. Research findings support the notion that incorporating a chimney in improved kilns enables efficient gas recirculation and internal combustion of pyrolysis gases; sustaining the pyrolysis process without requiring external heat, leading to superior efficiency and higher charcoal yield output compared to conventional kilns [56,60,61].

Additionally, our study revealed significantly lower levels of unburned wood and non-commercial charcoal in the improved kilns (Table 1). Specifically, the Mark V steel kiln and Green mad retort exhibited a twofold reduction in non-commercial charcoal compared to the traditional earth mound kiln, indicating that these kilns effectively mitigate the loss of charcoal associated with poor wood-to-charcoal conversion efficiency in traditional methods [62]. However, despite the higher efficiency observed in the Green mad retort, it recorded a higher amount of unburned wood, likely due to improper wood stacking and kiln construction design. Addressing these factors is crucial to achieving optimal carbonization control in improved kilns, leading to higher conversion efficiency and improved charcoal production.

3.2. Carbonization time

Significant ($P < 0.001$) variations in carbonization time among different kiln technologies were observed (Fig. 4). Results of the study showed the MRV steel kiln exhibited significantly ($P < 0.001$) the shortest carbonization time (40 h), followed by the Casamance kiln (60 h), traditional Earth mound kiln (120 h), and Green mad retort kilns (130 h). Notably, the longer carbonization time in the Green mad retort kilns can be attributed to extended cooling hours (84 h) and an effective carbonization time of 46 h. Technological advancements, improved insulation, and enhanced control mechanisms in the improved kiln likely contributed to this efficiency.

Table 1
Mean ± SE values of charcoal yield and yield components of different charcoal-making approaches using *Acacia decurrens* at Fagta lokoma district, North Western, Ethiopia ($n = 12$).

Kiln type	wood weight	Moisture content (%)	Charcoal yield(kg)	Unburned wood(kg)	Noncommercial charcoal(kg)	Efficiency (%)
Traditional	2750	15.22 ± 0.03 a	552.38 ± 1.01^{d}	47.8 ± 0.15b	30.6 ± 0.06^{a}	24.19 ± 0.36^{d}
GMDR	2750	15.12 ± 0.05^{a}	815.8 ± 0.17^{b}	74.2 ± 0.17^{a}	15.4 ± 0.09^{c}	36.14 ± 0.02^{b}
Casamance	2750	15.20 ± 0.03^{a}	786.5 ± 0.25^{c}	25.5 ± 0.26^{d}	20.2 ± 0.17^{b}	34.07 ± 0.02^{c}
MRV steel	2750	15.20 ± 0.03^{a}	957.7 ± 0.29^{a}	29.6 ± 1.00^{c}	13.2 ± 0.17^{d}	41.57 ± 0.03^{a}
P- Value	ns	ns	***	***	***	***
CV (%)		0.03	0.1	0.7	1.1	0.1

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; ***: $P \leq 0.001$.

Previous studies also support this explanation, emphasizing the positive impact of improved airflow control on carbonization performance, where the redirection of hot flues back into the kiln enhances efficiency and leads to shorter carbonization times [20,52,53,63].

Improved kilns showed significant reductions in carbonization time compared to the traditional Earth mound kiln, with a 66% decrease compared to the MRV steel kiln and a 50% decrease compared to the Casamance kiln. This indicates a considerable variation in the carbonization time and effectiveness of these kilns for charcoal production. Kilns with shorter carbonization times, such as the Casamance and Mark v steel kiln, offer potential advantages in terms of time and resource utilization, allowing for faster production and potentially higher throughput. The findings of this study have important implications for smallholder farmers and charcoal producers. The time saved through improved kilns could provide charcoal producers with the opportunity to engage in other livelihood activities, further enhancing their overall income and livelihood sustainability.

3.3. *Livelihood benefit*

The one-way analysis of variance test revealed a significant ($P < 0.001$) increase in charcoal production per hectare for the Mark V steel kiln (7694.1 sacks ha^{-1}), followed by GMDR (6526.7 sacks ha^{-1}), Casamance (6508.9 sacks ha^{-1}), and traditional Earth mound kiln (4734.7 sacks ha^{-1}) (Fig. 5a). This indicates an increase of 1774–3259.4 sacks ha^{-1} compared to traditional techniques, underscoring the importance of improved kilns for maximizing land benefits and reducing deforestation. These findings align with previous research, which also demonstrated that improved kilns yield more charcoal compared to traditional kilns [7,43,46]. Furthermore, traditional Earth mound kilns require 0.37 ha–0.62 ha of additional land to achieve the same charcoal production per hectare as improved kilns. Earlier studies have indicated that traditional kilns consume 0.1 ha of woodland to produce one tonne of charcoal, whereas improved kilns only require 0.05 ha [64].

Moreover, the analysis demonstrated that Mark V steel kilns generated the highest average charcoal income (284,824.4 ETB ha^{-1}), followed by Green mad retort (144,660.7 ETB ha^{-1}) and Casamance (123,943 ETB ha^{-1}), while traditional Earth mound kilns yielded the lowest charcoal income (71,580.5 ETB ha^{-1}) (Fig. 5b). In comparison, under the previous system of traditional earth mound kiln production, smallholder charcoal producers earned 63,963 ETB *from Acacia decurrens* small-scale plantation-based charcoal production [37]. Our research indicates that using traditional Earth mound kilns for charcoal production by smallholders and local producers leads to a substantial loss of charcoal income (52,362–213,244 ETB ha^{-1}). In contrast, improved kilns facilitate the establishment of a value chain for green charcoal and help mitigate unintended consequences, such as increased deforestation, due to higher profit margins for producers [63]. Furthermore, implementing energy-saving technologies in smallholder households has been suggested to boost the demand for biomass products and increase the availability of biomass residues for market supply instead of domestic use [3].

Fig. 5c depicts a notable increase in charcoal income from improved kilns at the district level, ranging from 91.2 to 371.4 million Ethiopian birr. The Green mad retort and Casamance improved kilns demonstrated positive effects on charcoal income, with increases of 36.2% and 102.1% at the hectare and district levels, respectively. Among the improved kilns, the MRV steel kiln showed the most remarkable boost in charcoal revenue, reaching 172.05% (Fig. 5b and c). The benefits derived from charcoal income outweighed those from conventional earth mound kilns by two to four times. These findings align with a case study conducted in the Nyaruguru and Nyamagabe districts of the Southern province of Rwanda, which demonstrated that improved charcoal-making techniques led to increased charcoal production and reduced air pollution [65]. The same study revealed that from one cubic meter of wood, a minimum of three bags of charcoal and 15 L of tar could be obtained, comprising the key components responsible for greenhouse gas emissions. Additionally, the chimneys of the Casamance and MRV portable steel kilns, made of superimposed metal barrels, enabled the collection

Fig. 4. Carbonization time of the different charcoal-making kilns at Fagta lokoma district, North Western, Ethiopia. Columns with different letters are significantly different at $P < 0.05$. MRV: Mark v steel kiln; Error bars: mean ± SE.

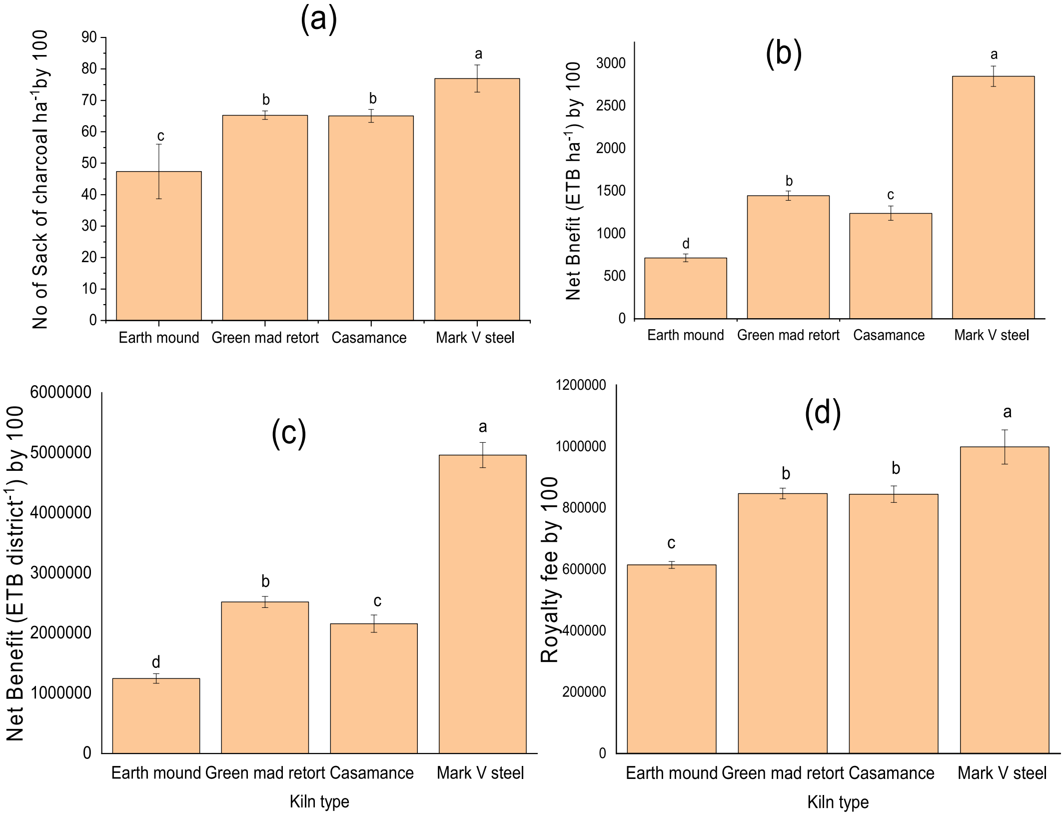

Fig. 5. Livelihood benefits of charcoal production from the different charcoal-making kilns: number of sack of charcoal ha^{-1} by 100 (Fig. 5a), net benefit (ETB ha^{-1}) by 100 (Fig. 5b), net benefit (ETB district^{-1}) by 100 (Fig. 5c), royalty fee by 100 (Fig. 5d). Columns with different letters are significantly different at $P < 0.05$. MRV: Mark v steel kiln; Error bars: mean ± SE.

of wood vinegar, which could be utilized for insect pest and crop disease control [17].

The study also observed that improved charcoal-making kilns increased government royalty fee revenue obtained from taxing charcoal production. Utilizing smallholder *Acacia decurrens* in improved kilns resulted in a significant rise in royalty fees, ranging from 61.4 million to 99.8 million ETB, leading to an income advantage of 38.18 million ETB (Fig. 5d). This evidence emphasizes the potential revenue loss the government could experience if the charcoal production system remains traditional. By adopting improved kilns, charcoal production can be sustained throughout the year, providing consistent benefits, income security, and resilience. Furthermore, the involvement of women in charcoal production extends their role beyond harvesting, which has positive implications for their livelihoods [66].

Furthermore, charcoal harvesting from improved kilns particularly, MRV steel kilns, become very easy and free from soil mixing and other unwanted debris (Fig. 6a) and even improved kilns opens an opportunity for womens to engage in charcoal harvesting

Fig. 6. Charcoal from different charcoal production kilns: MRV steel kiln (a), women loading charcoal to sack (b), charcoal from Green mad retort kiln (c), and teff straw and soil used for pile coverage (d). *Photo credit researcher, (2022).*

process or charcoal loading to sacks (Fig. 6b). Similarly, significant numbure of sack of charcoal were produced from Green mad retort kilns (Fig. 6c). Notably, improved kilns, except for the Casamance kiln, reduced the cost of teff straw and soil digging, which are essential expenses for traditional earth mound kilns. The MRV steel and Green mad retort kilns eliminated the need for teff straw and soil digging when compared to traditional earth mound kilns (Fig. 6 d). Traditional Earth mound kilns, on the other hand, required expenses of approximately 16,800 ETB for teff straw and 1500 ETB for soil mining at the hectare level, necessary for pile coverage and ensuring proper air entrance to the kiln. Improved charcoal-making kilns offer the possibility to increase charcoal production while reducing associated expenses [67]. While Green mad retort kilns are stationary once constructed and require a steady supply of *Acacia decurrens* dry wood in one location, this may not be suitable for the study area, where charcoal production takes place on different farms. Therefore, portable and easy-to-relocate kilns, such as the MRV steel and Casamance improved kilns, are more suitable for carbonizing *Acacia decurrens* wood into charcoal in various farmland areas.

Computing the costs at the district level revealed that the total costs of teff straw and soil digging for Earth mound kilns were 29.26 million and 2.61 million ETB, respectively. Improved kilns, which do not require teff straw and soil for coverage, effectively minimized these costs. Moreover, the Green mad retort kiln (GMDR) and MRV steel kiln achieved labor cost reductions of 25% and 50%, respectively, for cross-cutting logs compared to traditional earth mound kilns. These cost savings were due to the use of longer logs in the GMDR kiln (more than 1 m in size) and the MRV steel kiln (50–80 cm size of logs), which required less time and labor for cross-cutting. In contrast, traditional Earth mound kilns utilized shorter cross-cut logs (30–50 cm), leading to extended time and higher labor costs during the cross-cutting process. The study suggests the government should consider subsidizing the introduction of improved kilns to improve local smallholders' livelihoods and increase government revenue from small-scale *Acacia decurrens* plantation charcoal sales. Supporting traditional smallholder charcoal producers indirectly could reduce health facility expenditures due to environmental pollution from traditional earth mound kilns. To boost the effectiveness and acceptance of advanced charcoal production technology, a holistic strategy is needed. Governments should design and implement training programs to educate smallholder charcoal producers about the benefits and proper usage of improved kilns. This will enhance their understanding of sustainable charcoal production techniques and lead to a reduction in deforestation and greenhouse gas emissions. Governments must also establish policies and regulations that encourage the use of improved kilns and discourage traditional, environmentally harmful methods. This can include regulations on forest protection, emission standards, and sustainable land management practices. Another solution to improve the adoption of kilns is to promote the creation of fair and transparent market systems that incentivize environmentally friendly practices. By supporting such market systems, governments can encourage smallholder charcoal producers to embrace improved kilns and sustainable production methods, as they will be rewarded for their eco-conscious approach. This will not only benefit the environment but also create a positive economic environment that motivates producers to transition towards more sustainable charcoal production.

3.4. Greenhouse gas emission in kilogram per tonne of charcoal produced

Table 2 presents the emissions of selected gases from the different charcoal kilns studied. The results show a significant difference ($P < 0.001$) in the emission of greenhouse gases, with the lowest emissions observed in the following order: MRV steel < GMDR < Casamance < traditional Earth mound kilns. The study shows the improved kilns demonstrated remarkable reductions in emissions, ranging from 46% to 57.9% for CO_2, 29.4%–56.6% for CO, 61.7%–86.1% for NO, 56.6%–86.2% for NOx, 41%–62.8% for SO_2, and 35.7%–57% for CH_4. This indicates that the study highlights the importance of developing and adopting improved kiln technologies to foster a more sustainable approach to charcoal production. By reducing emissions, these technologies play a crucial role in creating a greener and environmentally friendlier charcoal production process, leading to a decrease in the adverse effects on air quality. This can lead to the development of more stringent emission standards and incentives for the transition to cleaner production methods. Our findings align with the research's initial hypothesis and are consistent with previous research studies [49–52,68]. Moreover, another study indicates that improved charcoal-making kilns exhibit comparable mean emission factors (kg $tonne^{-1}$ charcoal) for various gases: carbon dioxide (CO_2) - 1950 ± 209, carbon monoxide (CO) - 157 ± 64, and methane (CH_4) - 24 ± 17, compared to traditional kilns, which display higher emission factors CO_2 - 2380 ± 973, CO - 480 ± 141, and CH4 - 54 ± 29 [49]. In a separate research study examining commonly used charcoal-making kilns in Kenya and Brazil, the reported pollutant levels per tonne of charcoal produced

Table 2

Mean ± SE values of selected greenhouse gas emission in kilogram per tonne of charcoal produced from *Acacia decurrens* species using different charcoal-making kilns at Fagta lokoma district, North Western, Ethiopia (n = 12).

Kiln type	CO_2	CO	NO	NO_x	SO_2	CH_4
Traditional	2439.43 ± 26.35^{a}	474.57 ± 19.4^{a}	2.38 ± 0.04^{a}	2.77 ± 0.10^{a}	0.70 ± 0.03^{a}	51.00 ± 0.21^{a}
Casamance	1300.47 ± 15.54^{b}	262.93 ± 9.04^{b}	0.91 ± 0.05^{b}	1.20 ± 0.06^{b}	0.41 ± 0.03^{b}	32.77 ± 0.67^{b}
GMDR	1252.47 ± 8.22^{b}	220.17 ± 4.97^{bc}	0.36 ± 0.04^{c}	0.67 ± 0.11^{c}	0.37 ± 0.03^{bc}	27.40 ± 0.31^{c}
MRV steel	1027.13 ± 3.02^{c}	180.43 ± 2.29^{c}	0.33 ± 0.02^{c}	0.38 ± 0.05^{c}	0.26 ± 0.01^{c}	21.83 ± 0.07^{d}
P-value	***	***	***	***	***	***
CV	1.8	7.2	6.7	11.2	10.05	2.02

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; CO_2: carbon dioxide; CO: carbon monoxide; NO: nitrogen monoxide; NO_x: nitrogen dioxide; SO_2: sulphur dioxide; and CH_4: methane; ***: $P \leq 0.001$.

exhibited also a wide range: 543–3027 kg for CO_2, 32–62 kg for CH_4, 143–373 kg for CO, 24–124 kg for total nonmethane organic compounds, 0.011–0.30 kg for N_2O, and 0.0054–0.13 kg for NO_x. [42].

Furthermore, the study analyzed and compared gas emissions at both hectare and district levels (Fig. 7). The results revealed substantial variations in emissions, which is consistent with the findings presented in Table 2. The analysis of variance outcomes for gas emissions raised concerns as the emission levels of gases were notably higher than the charcoal production levels in kilograms per hectare (kg ha^{-1}). It was observed that the emission of carbon dioxide (CO_2) was found to be 80818.33 kg ha^{-1} for traditional Earth mound kilns, 63657.90 kg ha^{-1} for Casamance kilns, 59105.90 kg ha^{-1} for Green mad retort kilns, and 58989.87 kg ha^{-1} for MRV steel kilns (Fig. 7a). The highest emissions of carbon monoxide (CO) and methane (CH_4) were observed with earth mound kilns at 15706.73 kg ha^{-1} and 1689.40 kg ha^{-1}, respectively, followed by Casamance kilns (12866.97 kg ha^{-1} and 1602.73 kg ha^{-1}) and Green mad retort kilns (10389.83 kg ha^{-1} and 1292.93 kg ha^{-1}) (Fig. 7a). The MRV steel kiln exhibited the lowest emissions of CO and CH_4 at 10361.27 kg ha^{-1} and 1252.53 kg ha^{-1}, respectively. Similar emission trends per hectare were also observed for nitrogen monoxide (NO), nitrogen dioxide (NO_x) and sulphur dioxide (SO_2) (Fig. 7b).

Furthermore, the total CO_2 emissions in kilograms per district (kg $district^{-1}$) were 140.7 million for traditional Earth mound kilns, 110.8 million for Casamance kilns, 102.9 million for Green mad retort kilns, and 102.7 million for MRV steel kilns (Fig. 7c). The traditional Earth mound kilns exhibited the highest CH_4 emissions at 2.9 million (kg $district^{-1}$), while the MRV steel kiln demonstrated the lowest emissions at 2.2 million (kg $district^{-1}$). Emission of nitrogen monoxide (NO), nitrogen dioxide (NO_x) and sulphur dioxide (SO_2) at district level increased by 1741.8 times compared to their values at hectar level for all charcoal making kilns; were the lowest emission values for those gases were recored in the order of MRV steel kiln < Green mad retort < Casamance and traditional earth mound kilns (Fig. 7d). The lower selected gas emissions from improved kilns can be ascribed to their enclosed design, controlled airflow system, efficient heat utilization, and gas recycling capabilities [20,42,58,59,65]. The enclosed design ensures that the carbonization process takes place within a sealed container, effectively containing the gases produced during carbonization and preventing their release into the atmosphere. The controlled air supply also guarantees that the carbonization process occurs at the optimal temperature and with sufficient oxygen for complete combustion [20]. In contrast, Earth mound kilns rely on natural convection for airflow, which can be unpredictable and may lead to incomplete combustion and increased emissions [43]. Moreover, the improved kilns are engineered to effectively capture and utilize the heat generated during the carbonization process. This leads to higher temperatures within the kiln, aiding in reducing emissions by promoting a more efficient conversion of wood or biomass into charcoal [59,63]. The combination of these design enhancements results in the observed significant decrease in gas emissions, making the improved kilns a more environmentally friendly option for charcoal production.

The current study confirms that traditional charcoal production methods contribute significantly to greenhouse gas (GHG) emissions, which in turn can contribute to climate change and environmental degradation. The release of these gases, especially CO_2

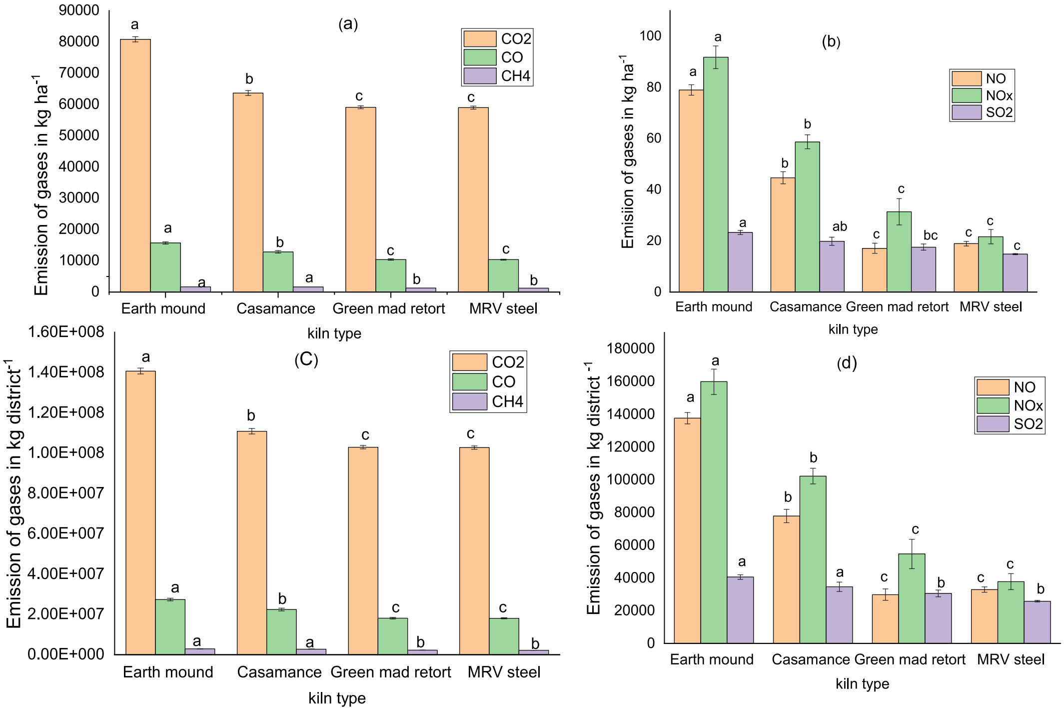

Fig. 7. Mean ± SE values of selected greenhouse gases in (kilogram) from Acacia decurrens charcoal of different charcoal-making approach: emission of CO_2, CO, CH_4 in kg ha^{-1} (a), emission of NO, NO_x, SO_2 in kg ha^{-1} (b), emission of CO_2, CO, CH_4 in kg $district^{-1}$ (c), emission of NO, NO_x, SO_2 in kg $district^{-1}$ (d). CO_2: carbon dioxide; CO: carbon monoxide; NO: nitrogen monoxide; NO_x: nitrogen dioxide; SO_2: sulphur dioxide; and CH_4: methane. Columns with different letters are significantly different at $P < 0.05$. MRV: Mark v steal kiln; Error bars: mean ± SE.

and CH_4, can exacerbate the greenhouse effect and lead to global warming [19,42]. Moreover, the emissions of NOx, SO_2, and CO can contribute to air pollution, leading to adverse effects on air quality and human health [69]. Failure to control and regulate emissions from traditional charcoal production systems can have also adverse effects on human health, including short-term issues like conjunctivitis, headaches, sore throats, and allergic skin reactions, and long-term consequences like loss of coordination, liver damage, and damage to the central nervous system [69–71]. These results underscore the importance of transitioning from traditional Earth mound kilns to more efficient and environmentally friendly alternatives, such as the MRV steel and GMDR kilns. The significant reductions in greenhouse gas emissions achieved by the improved kilns highlight their potential to mitigate the impact of charcoal production on climate change and emphasize the urgent need for the widespread adoption of these technologies. This can lead to more widespread environmental benefits and contribute to global efforts to combat climate change.

Additionally, the findings from the current study align with the emphasis on developing a sustainable agricultural farming system and promoting renewable and clean energy production [72–74]. While the study focuses on a specific region, its findings are likely to be relevant to other countries and regions where traditional charcoal production methods are still in use. As such, the study contributes to the broader understanding of the environmental impact of charcoal production and the potential for improved kilns to mitigate emissions. The study further highlights the importance of continued research and development in the field of charcoal production technologies. Advancements in kiln designs, burner systems, and emission control mechanisms can further enhance the efficiency and environmental performance of charcoal production processes.

4. Conclusion

In conclusion, the study unequivocally establishes that improved charcoal-making kilns yield significant benefits over traditional Earth mound kilns. These advantages encompass higher conversion efficiency, increased charcoal yields, and reduced wood consumption. From an economic perspective, smallholder charcoal producers can achieve higher income and cost savings. On the environmental front, these improved kilns contribute to mitigating greenhouse gas emissions, fostering climate resilience, and supporting sustainable low-carbon growth. Altogether, improved charcoal-making kilns offer a promising solution to boost economic prosperity and promote environmental conservation in the charcoal production sector.

To foster the widespread adoption of improved kilns, governments ought to implement comprehensive training programs, capacity-building initiatives, and financial incentives targeting smallholder charcoal producers. Simultaneously, establishing supportive policies, regulations, and institutions as well as improved access to finance, and facilitating market linkages will play a pivotal role in promoting sustainable charcoal production. Additionally, through collaborative efforts, policymakers, researchers, and charcoal producers can work together to promote the widespread adoption of improved charcoal-making kilns. This collective action will steer the sector towards a brighter and more environmentally friendly path, driving meaningful change and fostering a more sustainable and eco-conscious approach to charcoal production.

Author contribution statement

E T, a Ph.D. candidate specializing in forest and livelihood at the University of Gondar, Ethiopia, has made significant contributions to the conception and designed the experiment, pereformed the experiment, analyzed and interpreted the data as well as wrote the paper. Professor S S from Soka University, Japan, have played crucial roles in conception and designed the experiment, analyzed and interpreted the data, contributed regent, material, analysis tool or data, and wrote the paper; S A, an associate professor at Bahirdar University in research conception and designed the experiment, analyzed and interpreted the data and wrote the paper; E B, an Associate Professor from Adama Science and Technology University made contributions research conception and designed the experiment, analyzed and interpreted the data and wrote the paper; Associate Professor A A from the University of Gondar contributed in research conception and designed the experiment, analyzed and interpreted the data and wrote the paper; and Professor B B from Injibara University, Ethiopia have also made valuable contributions, in the research conception and designed the experiment, analyzed and interpreted the data and wrote the paper.

Data availability statement

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

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Declaration of competing interest

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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