Environ Monit Assess (2024) 196:162
https://doi.org/10.1007/s10661-024-12354-2

RESEARCH

Enhancing wood to charcoal conversion efficiencies from smallholder plantation charcoal production systems: Implications for carbon emissions and sustainable livelihood benefits in North Western Ethiopia

**Ewunetu Tazebew · Solomon Addisu ·
Eshetu Bekele · Asmamaw Alemu ·
Berhanu Belay · Shinjiro Sato**

Received: 23 October 2023 / Accepted: 11 January 2024 / Published online: 17 January 2024

Abstract Charcoal production stemming from small-scale Eucalyptus camaldulensis plantations has brought about significant socio-economic benefits and improved livelihoods in Ethiopia. Nevertheless, the current practice involves the use of traditional earth mound kilns, leading to inefficiencies, reduced charcoal income, and environmental pollution. This research aims to assess charcoal conversion efficiency, perform a cost–benefit analysis, and measure gas emissions from improved charcoal-making kilns sourced from Eucalyptus camaldulensis small-scale plantations in comparison to traditional earth mound kilns in northwestern Ethiopia. A one-way analysis of variance (ANOVA) was executed, with a significance level set at 0.05. The study results indicate a significant ($P < 0.001$) disparity in charcoal conversion efficiency across the various tested kilns, with the ranking as follows: Green mad retort kiln (33.7%) > Casamance kiln (32.09%) > MRV steel kiln (28.25%) > traditional earth mound kilns (23.55%). The improved charcoal-making kilns enhanced wood-to-charcoal conversion efficiency by 20–43% compared to traditional earth mound kilns. In terms of financial viability, Casamance improved kilns generated the highest equivalent annual charcoal income (117,126.9 ETB/year), followed by Green Mad Retort (82,893.8 ETB/year) and MRV steel kilns (58,495.9 ETB/year). As anticipated, traditional earth mound kilns yielded the lowest net present value (47,304.3 ETB/year). Traditional earth mound kilns also exhibited significantly longer carbonization times ($P < 0.001$), taking 3.6 times longer than the Mark V kiln and 2 times longer than the Casamance kiln. Furthermore, the statistical analysis demonstrated that improved charcoal-making technology reduced carbon dioxide (CO_2) emissions by 36.1–50.7%, carbon monoxide (CO) emissions by 39.2–54.3%, and methane (CH_4) emissions by 29.6–47%. In conclusion, the use of improved charcoal-making kilns has demonstrated significant enhancements in charcoal conversion efficiency, charcoal income, and environmental sustainability. Given these positive outcomes, we strongly recommend a decisive transition from

---

E. Tazebew (✉) · A. Alemu
College of Agriculture and Environmental Science,
University of Gondar, Gondar, Ethiopia
e-mail: jackmanof23@gmail.com

E. Tazebew · B. Belay
College of Agriculture, Food and Climate Sciences,
Injibara University, Injibara, Ethiopia

S. Addisu
College of Agriculture and Environmental Science, Bahir
Dar University, Bahir Dar, Ethiopia

E. Bekele
School of Applied Natural Sciences, Adama Science
and Technology University, Adama, Ethiopia

S. Sato
Faculty of Science and Engineering, Soka University,
Tokyo, Japan

traditional to cleaner, sustainable, and less emissions-intensive charcoal making kilns.

Keywords Charcoal · Efficiency · Environment · *Eucalyptus camaldulensis* · Greenhouse gas emission · Improved charcoal-making kilns · Income

Introduction

Charcoal plays a crucial role in bolstering the income of rural households, serving as an essential energy source, and delivering a range of socio-economic advantages to their livelihoods (Ababa, 2019; Smith et al., 2019; Tadesse et al., 2019; Andaregie et al., 2020; Thabane, 2020; Bekele & Kemal, 2022). Charcoal is the result of wood undergoing carbonization, a process where it is burned with limited oxygen (Koech et al., 2021).

The global production and consumption of charcoal have seen a significant increase, surging from 17 million tons in 1964 to a current 53 million tons, with Sub-Saharan Africa contributing to 61 percent of this production (Kenne et al., 2022). Roughly one-third of the world's population relies on inefficient cook stoves for cooking and heating, using unsustainable solid biomass. In Africa, approximately 195 million people, constituting around 20 percent of the continent's population, are involved in charcoal production (Dam, 2017). Kenya alone has 500,000 people engaged in charcoal production activities (Njenga et al., 2013).). In many tropical countries, including Tanzania and Mozambique, woodlands can regenerate within 8–30 years after trees are harvested for charcoal production (Chidumayo & Gumbo, 2013; Woollen et al., 2016). Given the rising trends in urbanization and population growth, coupled with the fact that charcoal produces less smoke and is relatively more affordable compared to modern energy sources, the demand for charcoal is expected to double in the upcoming decade (Neuberger, 2015; Doggart & Meshack, 2017; Raza et al., 2022).

In Ethiopia, much like in other regions, charcoal production serves as a vital source of income for numerous rural households, constituting either their primary or secondary livelihood activity. This practice provides essential cash income to a substantial number of households in rural areas. Remarkably, Ethiopia ranks as the third-largest charcoal producer globally, trailing only behind Brazil and Nigeria, boasting an estimated production exceeding 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 and 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). Despite the anticipation of a twofold increase in demand for charcoal in developing nations in the forthcoming decades, charcoal producers lack access to essential knowledge and advanced technologies for sustainable charcoal production. For instance, the key barriers to the increased adoption of charcoal making kilns in Ethiopia encompass the lack of awareness among smallholder charcoal producers concerning the economic and environmental benefits associated with improved kilns (Bekele & Kemal, 2022). Furthermore, challenges like substantial initial investment costs, a lack of proficiency among charcoal producers, and insufficient government attention to the charcoal industry significantly impede widespread usage (Andaregie et al., 2020). As a result, charcoal producers in developing countries including Ethiopia continue to employ inefficient charcoal-making kilns (Baumert et al., 2016; Zorrilla-Miras et al., 2018; Ferede et al., 2019; Rodrigues & Junior, 2019; Koech et al., 2021a; Bekele & Kemal, 2022) and there is no intial incentive or regulation to produce charcoal efficiently in subsharan Africa where food insecurity and poverty is sever (Bekele & Kemal, 2022).

Hence, the utilization of inefficient and unsustainable traditional earth mound kilns for charcoal production results in low wood-to-charcoal conversion efficiency, diminished charcoal income, increased greenhouse gas emissions, and adverse effects on the health of the charcoal producer community. Emissions from traditional charcoal-making were reported 71.2 million tonnes of carbon dioxide

---

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

and 1.3 million tonnes of methane (Chidumayo & 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 6–9 kg CO2 eq along its whole life cycle (Dam, 2017).

Similarly, in 2010, Ethiopia recorded greenhouse gas emissions of 150 $MtCO_2e$. Projections indicate that, under a business-as-usual scenario, this figure is expected to more than double to 400 $MtCO_2e$ by 2030 (Selvakkumaran and Silveira, 2019; M. A. Worku, 2020). Notably, a significant portion of these emissions, accounting for 37% of the total, is attributed to livestock and forest degradation resulting from fuelwood cutting and charcoal production, contributing 65 Mt CO_2e and 55 Mt CO_2e, respectively (Selvakkumaran & Silveira, 2019; M. A. Worku, 2020). To address this, Ethiopia has established a target to reduce emissions in 2030 to approximately 150 Mt CO_2e, which is roughly 250 Mt CO_2e less than the business-as-usual projection (Ethiopia, 2019). Ethiopia has responded to this challenge through a combination of conservation efforts and policy initiatives aimed at mitigating greenhouse gas emissions from agricultural activities. They have integrated climate-smart agriculture into various national policies, strategies, and programs (César & Ekbom, 2013; Yimer, 2016) with the overarching goal of enhancing climate resilience and fostering a more sustainable, low-carbon growth trajectory, placing a strong emphasis on environmentally friendly agricultural practices. 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. The scientific enhancement of traditional charcoal-making methods is not only an environmentally responsible step but also a vital one for economic development and achieving greenhouse gas emission reduction targets. It embodies a proactive approach to addressing a range of interconnected issues, from environmental conservation to economic well-being and climate change mitigation. By enhancing traditional charcoal production methods, there is a potential to reduce the demand for cutting down forests for fuelwood. This helps conserve vital forest ecosystems and biodiversity while mitigating the adverse environmental impact associated with deforestation.

Prveousely, there have been attempts in conversion of fuel wood to charcoal using improved charcoal-making kilns in Africa (Jolien Schure et al., 2019), and retort kilns (Adam, 2009; Jolien Schure et al., 2019) in India. Nevertheless, there is a scarcity of scientific data in the literature that compares the efficiency of different improved charcoal kilns, their financial viability, and greenhouse gas emissions against conventional methods for producing renewable, cleaner, and sustainable charcoal (Jolien Schure et al., 2019). Previous studies assessing conversion efficiency (Kammen & Lew, 2005; Neufeldt et al., 2015) failed to account for factors such as the initial wood consumption for carbonization, unburned wood during the process, varying moisture levels in dry wood, wood diameter, tree species characteristics, and the carbonization process itself. These variables can result in differing levels of efficiency, economic benefits, and gas emissions. Moreover, past studies relied on indirect methods for estimating gas emissions instead of direct, on-site measurements from charcoal kilns (Chidumayo & Gumbo, 2013; Tassie et al., 2021). The financial profitability of different charcoal-making kilns has remained largely unaddressed. Therefore, there is a pressing need for a comprehensive comparative evaluation of efficiency and direct measurement of greenhouse gas emissions originating from a diverse range of charcoal-making kilns, encompassing advanced charcoal production technologies and conventional earth mound kilns. This undertaking is essential in identifying cost-effective, less emissions-intensive charcoal kilns, and sustainable solutions for charcoal production.

Charcoal production has been widely criticized for its potential negative impact on the environment, and there is a global call for its replacement. However, the scenario in the South Achefer district of Northwest Ethiopia presents a unique perspective compared to other charcoal-producing regions. In this locality, local smallholder farmers cultivate Eucalyptus camaldulensis tree species, raising them from nurseries, transplanting them to fields, and eventually harvesting them at the age of 5–7 years. These Eucalyptus tree growers not only sell the poles but also generate income from the residues left after harvesting, which are locally referred to as "Kirisite." This dual source of income from pole sales and charcoal production has proven to be a significant economic driver for the community. Moreover, a study conducted in northwestern Ethiopia has demonstrated that Eucalyptus cultivation contributes substantially to income and provides various socioeconomic benefits when compared to households that do not engage in tree planting (Abate et al., 2022; Addis et al., 2016; Mekonnen et al., 2007; Tesfaw et al., 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 et al., 2023; Tesfaw et al., 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 (Tesfaw et al., 2023).

Nonetheless, it is important to note that charcoal production in the South Achefer district primarily relies on inefficient traditional earth mound kilns. These outdated kilns have shown poor wood-to-charcoal conversion efficiency, resulting in reduced charcoal income, heightened greenhouse gas emissions, and exposing charcoal producers to health risks during the production process. To the best of the authors' knowledge, there has been no scientifically conducted research focused on enhancing the conventional charcoal-making method through the utilization of various improved charcoal pyrolysis technologies, neither in Ethiopia as a whole nor within the specific study area. Previous studies on *Eucalyptus* were focused on socioeconomic importance (Abate et al., 2022; Gizachew, 2017; Kebede, 2022; Tesfaw et al., 2021), challenges and opportunities (Tesfaw et al., 2021), value chain (Nacke, 2021), and its expansion (Molla et al., 2023). Given the enduring importance of *Eucalyptus camaldulensis* small-scale plantation-based charcoal production as a vital income and energy source in the region for the foreseeable future, transitioning from the current traditional earth mound kiln technology to improved charcoal production methods represents a potential avenue for enhancing efficiency in charcoal production. The examination of different charcoal-making technologies and their potential to reduce greenhouse gas emissions carries substantial environmental implications. Identifying technologies that are less emissions-intensive charcoal production approaches can contribute to mitigating the adverse effects of climate change and preserving local ecosystems. Investigating the cost–benefit analyses of different kilns is also vital for making informed decisions about investment in charcoal production. The findings can guide local producers and policymakers in choosing economically viable technologies and, in the process, enhance the economic sustainability of the charcoal industry in the study area. Thus, the present research was initiated to: (i) assess the advantages of different improved charcoal-making kiln technologies concerning wood-to-charcoal conversion efficiency in comparison to traditional earth mound kilns, (ii) examine the impacts of diverse improved charcoal-making technologies on the potential reduction of greenhouse gas emissions, (iii) evaluate the carbonization duration of various kilns, and (iv) investigate cost–benefit analyses of the different kilns and provide recommendations for the appropriate charcoal-making kiln technology in the study area.

Material and methods

Study area description

The research was carried out in the South Achefer district, situated in the West Gojam Zone of North Western Ethiopia, precisely located at 11°49′59.99" North latitude and 37°09′60" East longitude, as shown in Fig. 1. This study area is approximately 502 km away from Addis Ababa, the capital city of Ethiopia, and about 60 km from Bahir-Dar. It shares its boundaries with North Achefer to the North, Awi Zone to the South and West, and Mecha district to the East. Durbete serves as its administrative center and is subdivided into 20 rural and 2 urban Kebele administrations. The district has a total population of 163,052, comprising 78,839 men and 84,213 women, as reported by Dereje (2019). Among this population, roughly 16% reside in urban areas, while the remaining 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, mid-highland locally called "Woynadega" (87%) and lowland locally called "Kola" (13%). "Woynadega" refers

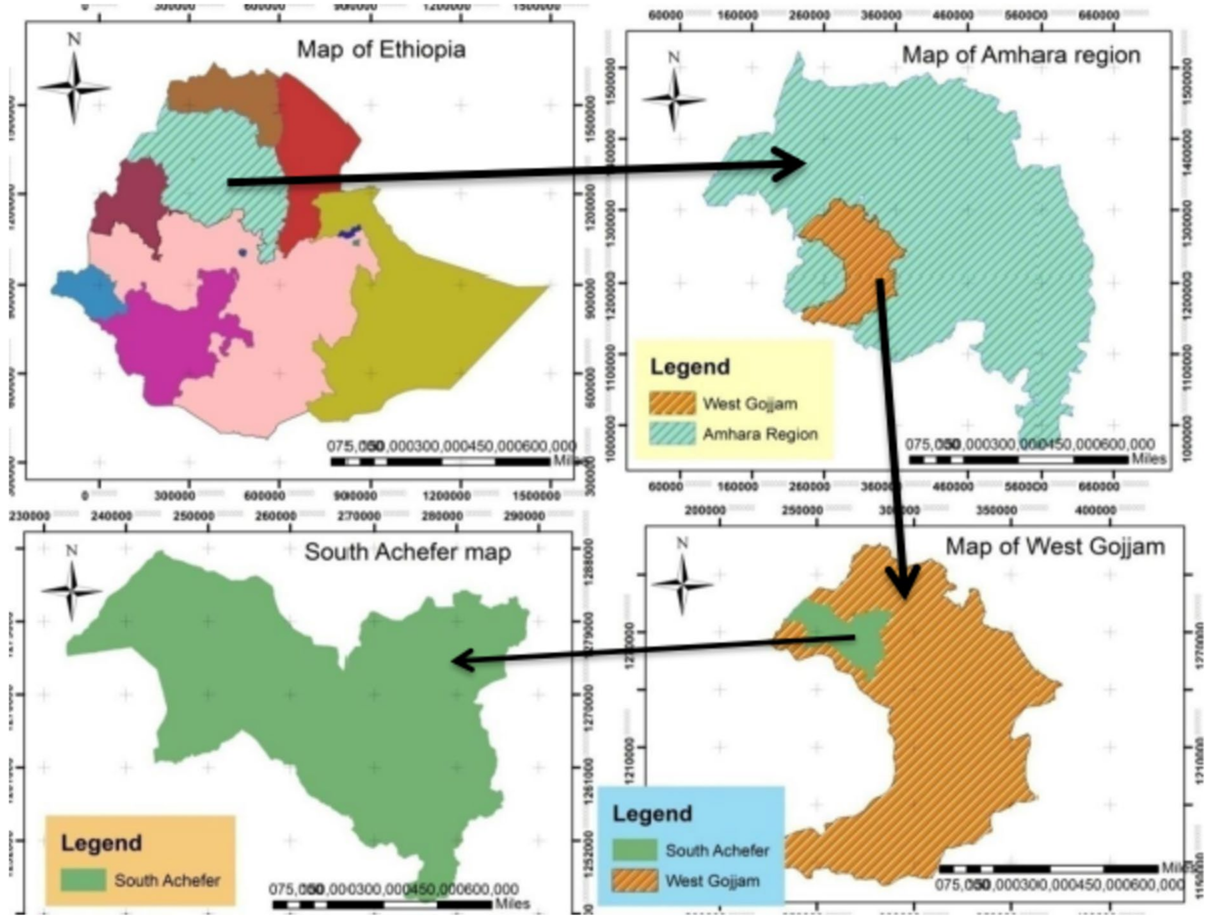


Fig. 1 Map of the study area. Source: Amhara Region Investment Bureau

to areas with altitudes between 1,500 and 2,300 m, while "kola" refers to areas with altitudes ranging from 500 to 1,500 m (Desta et al., 2023).

The annual temperature of the south Achefer district ranges from 18 to 28 oC with annual rainfall ranging between 1365 mm—1623 mm. Agricultural production is characterized by a mixed farming system in which crop production dominates over livestock rearing (Teshome et al., 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; (A. Worku et al., 2021; Molla et al., 2023; Tesfaw et al., 2023). The prolonged cultivation of eucalyptus smallholder plantations on agricultural land could potentially negatively affect the food supply in West Gojam due to the conversion of agricultural production to eucalyptus plantations. However, the income generated from eucalyptus smallholder plantations is higher compared to income from food crops (Abate et al., 2022; Addis et al., 2016; Mekonnen et al., 2007; Tesfaw et al., 2021). This increased income can be utilized to purchase food crops, and the surplus income may contribute to diversifying livelihoods and enhancing overall well-being(Addis et al., 2016).

Wood drying and wood diameter measurement

The moisture content and the diameter of the sampled wood represent crucial parameters when assessing the efficiency of wood-to-charcoal conversion in a given charcoal kiln. To address this,

Fig. 2 Existing traditional charcoal production technique on converted agricultural land (**a**) and around residential areas (**b**). Photo credit researcher (2022)

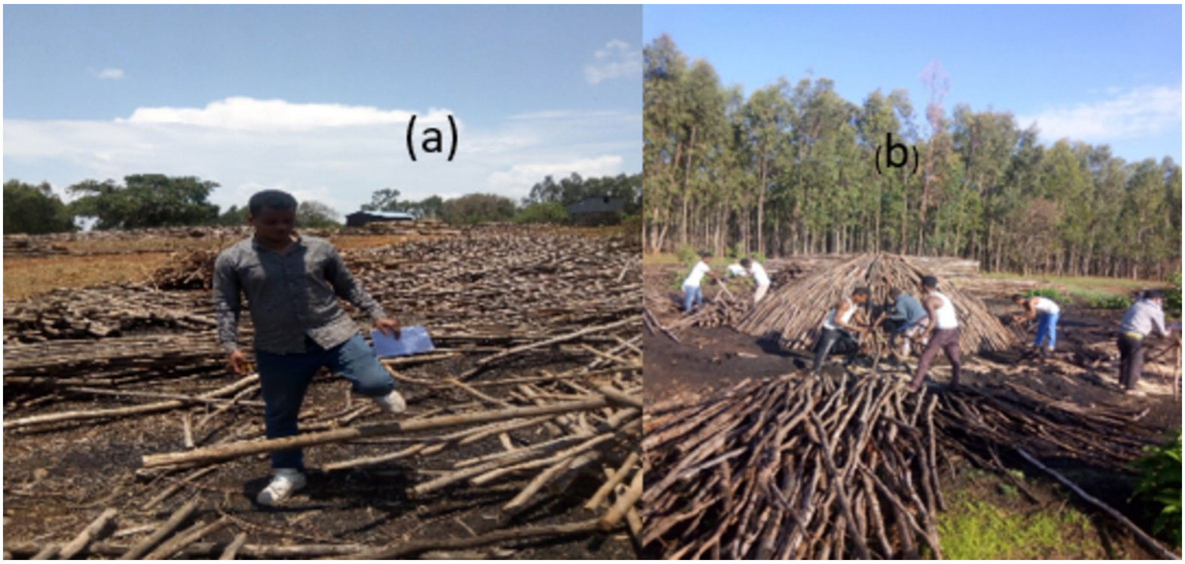


Fig. 3 Drying of wood (**a**) and the subsequent cross-cutting of the dry wood (**b**)

Eucalyptus camaldulensis wood sourced from smallholder plantations underwent a solar drying process lasting two to three weeks before initiating carbonization following methods similar to those employed in the local smallholder context (Fig. 3a). In the local smallholder setting, charcoal producers typically dry their wood for a period of two to three weeks after cutting trees on their farms and the dry wood is subjected to cross-cut in smaller size (Fig. 3b). This step are essential to reduce moisture content and, in turn, minimize heat energy wastage during the drying phase. The local charcoal producer believes that initiating carbonization of dry wood immediately after cutting results in lower charcoal yield due to high moisture content. Conversely, prolonged solar drying of wood for more than a month leads to similar issues, as excessively dry wood is prone to extensive burning. Consequently, we incorporate the local practice of an optimal drying time ranging from 2–3 weeks as the believed ideal wood drying phase for charcoal production.

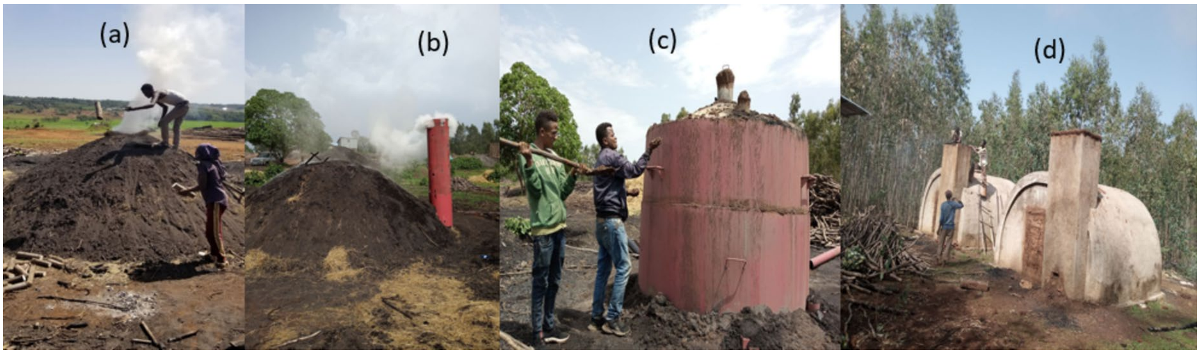


Fig. 4 the different charcoal production technology used in the current study; Earth mound kiln (**a**); Casamance (**b**); MRV steel (**c**); Green mad retort (**d**). Photo credit researcher (2022)

To assess moisture content, portable handheld moisture meters equipped with two penetrating probes were used to obtain three moisture readings from 10% of the dried Eucalyptus camaldulensis wood. These readings were taken on selected pieces of wood at the lower, middle, and upper sections of the dry logs following the methodology (Manaye et al., 2022). The process was repeated on the same pieces of wood to ensure that the moisture content of the dry wood was consistently below 20%. A final moisture reading was carried out just before the wood was arranged for immediate charcoal carbonization. Additionally, diameter measurements were conducted using diameter tape, following a similar methodology to the moisture measurements. It was determined that, on average, the sampled wood had a diameter of approximately four centimeters.

Charcoal production

Charcoal production was carried out using a uniform weight of Eucalyptus camaldulensis wood (3502 kg) in Durbete, South Achefer district, North Western Ethiopia, as depicted in Fig. 1. In this study, various charcoal production technologies were employed: traditional Earth mounds (Fig. 4a), Casamance (Fig. 4b), modified Mark V steel kilns (Fig. 4c) and Green Mad Retort Kilns (Fig. 4d). The charcoal production process were replicated three times for each charcoal production approaches, facilitating a comprehensive comparative analysis and accurate estimation of their efficiency, economic impact, and environmental benefits. In the current study, the charcoal production process for various charcoal production approaches involved collaboration with two experienced charcoal producers within the local context. The smallholder charcoal production process in this area differs from other regions where only experienced charcoal producers are involved in charcoal carbonization. In the local context, smallholder charcoal producers enlist the services of experienced charcoal producers at a rate of 10 ETB per bag, covering activities from charcoal carbonization to loading charcoal to bagging and we have factored this cost into the financial analysis of the different charcoal production approaches. Our collaboration with the charcoal producer spanned the entire process, from wood cross-cutting to the final charcoal output, aligning with our established methodologies for data collection making our experimental work more controlled than the normal local context.

Traditional earth mound kilns were exclusively used by local charcoal producers in North Western Ethiopia (Ferede et al., 2019; Bekele & Kemal, 2022). The operation of these kilns began with stacking wood in a conical shape on a well-prepared flat surface, with larger pieces placed in the center and covered with teff grass and soil to insulate the carbonizing wood, preventing excessive heat loss before carbonization.

The other charcoal making approaches used in the current study are improved charcoal making kilns which refer to advanced and more efficient designs for kilns used in the process of producing charcoal from biomass, such as wood or agricultural residues (Kammen & Lew, 2005). The charcoal-making process entails heating organic materials through pyrolysis, a low-oxygen environment, to transform them into charcoal a material with high carbon content (Mensah & Frimpong, 2018). The Casamance earth kiln employed in this study is a modified earth mound kiln equipped with a chimney affixed to one side (Fig. 4b). Another improved kiln used in this study is the modified MRV steel kiln (Mark V steel kiln) which is a portable steel kiln in the shape of a cylinder with a conical top (Fig. 4d). It features outer grooves filled with mud to secure the second ring and cover. Additional stiffening rings made from angle iron are welded to enhance stability and support the rings. The modified Mark V kiln comprises three interlocking parts: the lower ring, the upper ring, and the conical lid/cover at the top. On the other hand, the Green Mad Retort Kiln (GMDR) is a semi-industrial brick retort kiln with three sections: an external combustion chamber for using lower-quality wood or other biomass, a charcoal chamber, and a chimney incorporating a simple system for post-combusting the gases generated during carbonization. The construction of Casamance and MRV steel improved charcoal kilns was executed by the Ethiopian Rural Energy Development Promotion Center (EREDPC) under the auspices of UNDP projects and GMDR was onstructed by GIZ Ethiopia, with consultancy provided by Dr. Getachew Eshete. Kiln operation was overseen by operators from the ignition phase to the completion of carbonization for each kiln.

The completion of the wood-to-charcoal carbonization process was noted by the change in smoke color emanating from the improved kiln chimneys and natural outlets, transitioning to a light blue hue, indicating the carbonization's completion. In the case of traditional earth mounds, Casamance, and Mark V steel kilns, the reduction in the size of the piled wood to about two-thirds of its original size served as an indicator of the charcoal carbonization's completion. Once carbonization had finished, the chimneys and breathers were removed. Following the cooling of the charcoal, any remaining soil and unburned teff straw (in the case of traditional earth mounds and Casamance kilns) were cleared using spades and soil rakes. Unburned wood and non-commercial charcoal were segregated and separately weighed using a balance, for later use in the efficiency calculations of the various kilns employed in the study.

Efficiency and cost–benefit analysis

The efficiency of wood-to-charcoal conversion in the kilns stands as a pivotal factor in the decision-making process when selecting a particular charcoal-making kiln for investment. A greater charcoal conversion efficiency from a given kiln translates to increased charcoal sales and income. Bearing this parameter in mind, the wood-to-charcoal conversion efficiency of the kilns was calculated using (Girard, 2002).

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

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).

Conversely, achieving a greater wood-to-charcoal conversion efficiency does not guarantee a consistently positive income due to the specific cost dynamics associated with enhanced charcoal kilns. These costs encompass various aspects, including production costs (dry wood, bags, ropes, strings, teff straw, cutting tools, wood harvesting, and producer expenses), as well as the benefits from charcoal sales (valued at 65 Ethiopian Birr per bag during the study season). For ease of comparison, all expenses and benefits were taken into account. To address the time value of money, future cost and benefit values were discounted, allowing for more straightforward comparisons with current values, as recommended by (Whitman & Terry, 2012). A financial analysis technique known as Net Present Value (NPV) was employed to assess the various incentives associated with investing in different charcoal kilns. NPV calculates the net returns of the production system by discounting the flows of benefits and costs back to the year of establishment, using a suitable discount rate for Ethiopian conditions (10%) over the lifespan of each kiln. The cost–benefit analysis of improved and traditional charcoal-making technology was computed using the formula proposed by (Garrett et al., 2000; Whitman & Terry, 2012; Duguma, 2013).

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

where B = Total benefit generated from the investment, C = Total 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 et al., 2005)

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

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

Moreover, given the varying characteristics of charcoal-making kilns, including their useful life span, percentage of depreciation, and salvage values, we proceeded to calculate the equivalent annual charcoal income for all kilns using the following method:

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

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

Measurement of emission of gases from different charcoal production kilns

Emissions of specific gases, including methane (CH_4), carbon dioxide (CO_2), nitrogen monoxide (NO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), and carbon monoxide (CO), originating 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). The Istagemission gas chromatographic system is a portable handheld device designed for measuring various gases directly in field settings. To ensure accurate measurements, the istagemission gas chromatographic system was meticulously calibrated. This process involved positioning the equipment away from the emission source to establish a baseline, where oxygen concentration was determined to be in the range of 20.9% to 21%, while all other gases and particulate matter were recorded as 0% (Usui et al., 2018). Once the calibration was successfully executed, a metallic sampling probe was carefully introduced into a designated vent of each charcoal kiln. The recorded values were then allowed to stabilize over a five-minute period before being saved for subsequent analysis. At the of end of the testing period, conduct a clean air purge every 10 min before fully shutting down the analyzer. Additionally, replace the internal water trap as required, particularly if it displays cracks, accumulates a crusty layer of dust or particulates, or becomes wet. Carefully open the water trap and extract the inner plastic piece from the top half, wiggling it as you pull for easier removal. This will provide access to the filter cartridge.

The different gases emissions from each charcoal production approach were then divided by the charcoal yield produced from the respective charcoal production kilns to determine the emission per unit of charcoal produced (Pennise et al., 2001).These emission values were even further translated to year bases considering the total amount of charcoal produced in the study season. Then the different values of green house gases emmssion were multiplied by their respective global warming potential (GWP) to calculate total mass of CO_2-equivalents (CO_2e) that could be avoided in one year by transitioning from one earth mound kiln to one of each of the three improved kilns following (IPCC, 2006). Finally we sum up the total mass of CO_2-equivalents (CO2e) of each gresnhouse gases for each improved charcoal making kilns and substract it from the CO_2-equivalents fom the traditional earth mound kilns to get the avoided $CO_{2\text{-}}$equivalents (CO2e) from a given improved charcoal making approaches.

Carbon Dioxide Equivalent (CO2e) serves as a measure to quantify the global warming potential of diverse greenhouse gases by expressing their impact in relation to the amount of carbon dioxide (CO2) that would produce an equivalent warming effect over a specified time frame. This approach facilitates the comparison of different greenhouse gases on a standardized scale, streamlining the assessment and communication of their respective contributions to climate change. The Intergovernmental Panel on Climate Change (IPCC, 2006) has indicated a GWP for methane between 28–36 when considering its impact over a 100-year timeframe (GWP100) (indicating that one tonne of methane will result in the same warming effect as 28–36 tonnes of CO_2), nitrous oxide registers at 298, and certain highly potent F-gases have GWPs exceeding 10,000. Carbon dioxide serves as the reference, possessing a Global Warming Potential (GWP)

Table 1 Mean ± 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 ± 0.06^{a}	685.6 ± 2.60^{d}	64.40 ± 1.90^{c}	37.4 ± 0.83^{ab}	23.55 ± 0.05^{d}
GMDR	3502	15.00 ± 0.03^{a}	961.8 ± 3.27^{a}	122.4 ± 1.73^{d}	19.2 ± 0.62^{c}	33.70 ± 0.09^{a}
Casamance	3502	14.97 ± 0.03^{a}	940.8 ± 4.21^{b}	$46. \pm 0.35^{b}$	25.5 ± 0.50^{b}	32.09 ± 0.13^{b}
MRV steel	3502	14.95 ± 0.02^{a}	808.9 ± 2.02^{c}	173.7 ± 1.36^{a}	45.3 ± 5.43^{a}	28.25 ± 0.25^{c}
P- Value	3502	ns	***	***	**	***
CV (%)		0.44	0.63	2.5	15.1	0.88

Columns with different letters are significantly different at $P < 0.05$.GMDR: Green mad retort kiln; MRV: Mark v steel kiln; ns: not significant CV: Coefficient of variation; ***: $P \leq 0.001$

of 1, regardless of the chosen time period. CO_2 emissions contribute to elevated atmospheric concentrations that endure for thousands of years.

Statistical analysis

The gathered data underwent statistical analysis through SPSS version 26. A one-way analysis of variance test (ANOVA) was executed, with a significance level set at 0.05. In cases where noteworthy distinctions among various charcoal-making kilns were observed with a p-value less than 0.05, post-hoc mean separation was conducted using Tukey's Honestly Significant Difference (HSD) tests.

Results and discussion

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

The efficiency of converting *Eucalyptus camaldulensis* wood into charcoal using various improved charcoal-making kilns is summarized in Table 1. The study's results indicate that the improved charcoal-making technology kilns led to a significant ($P < 0.001$) increase in both charcoal conversion efficiency and charcoal yield. Remarkably, the kilns exhibited the highest charcoal conversion efficiency in the following order: 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 underscore that the Green mad retort kiln delivered the highest wood-to-charcoal conversion efficiency, whereas the traditional earth mound kiln exhibited the lowest conversion efficiency. In line with these results, field trials of charcoal production conducted in northern Madagascar using the Green mad retort (GMDR) external combustion chamber kiln achieved an efficiency of approximately 34% when sourced from plantation forests (Temmerman et al., 2019).

An analysis of charcoal yield reveals that improved charcoal-making technology requires a smaller quantity of wood to produce an equivalent quantity of charcoal compared to earth mound kilns. Our findings align with previous research on the efficiency of charcoal production kilns, showing favorable comparisons with studies (Kimaryo & Ngereza, 1989; Kammen & Lew, 2005; Adam, 2009; Jolien Schure et al., 2019). However, our results are higher in comparison to other studies (Mutimba & Barasa, 2005; Heinze et al., 2013; Luwaya et al., 2014; Morgan-Brown & Samweli, 2018; J Schure et al., 2021). Conversely, our findings are lower than those similar other reported research (Wartluft and White, 1984; Swami, 2009). The variability in findings across different studies can likely be attributed to factors such as the initial wood consumption required for carbonization, unburned wood during the carbonization process, varying moisture content in dry wood, wood diameter, tree species characteristics, and the carbonization process during charcoal production, all of which may differ across various locations (Ojelel et al., 2015; M Temmerman, 2016; Ferede et al., 2019; Charvet et al., 2022).

The Green mad retort improved kiln, using 2976 kg of anhydrous wood, consistently yielded an average of 961.88 kg (equivalent to 128.2 bags) of charcoal. In contrast, the traditional earth mound charcoal-making kiln at the study site, also employing

2976 kg of anhydrous wood, produced the lowest charcoal yield at 685.6 kg (equivalent to 97.95 bags) compared to the other kilns. Likewise, improvements in charcoal yield were observed with the Casamance kiln, producing 940.83 kg (or 125.4 bags), and the MRV-improved steel kiln, generating 808.96 kg (about 111.5 bags). It is worth noting that studies in this domain indicate that enhancing the conversion efficiency of traditional charcoal kilns from 15 to 25 percent could result in a substantial 40 percent reduction in the amount of wood required to produce the same quantity of charcoal (Dam, 2017). This could be beneficial in Ethiopia, where the demand for charcoal production is increasing from time time due to increasing population, deforestation of forest resources as well as the inefficiency of charcoal production using traditional methods nationwide (Brobbey et al., 2019; Guta, 2014). The price of charcoal continues to rise, emphasizing the need to enhance charcoal production mechanisms. The increased efficiency observed in improved charcoal-making kilns can be attributed to their thoughtful design. The radial arrangement of wood stringers and the presence of a circumferential air space beneath the apron ensure a steady, uninterrupted flow of air and gas, resulting in consistent carbonization. Additionally, these advanced kilns incorporate a chimney on one side, which effectively encourages a reverse airflow, maintaining the integrity of the circumferential air chamber throughout the entire burning cycle, thus sustaining continuous ventilation (Mabonga-Mwisaka, 1983; Kimaryo & Ngereza, 1989). In contrast, traditional earth mound kilns tend to be less efficient and wasteful, mainly due to excessive air circulation within the mound, which leads to reduced charcoal yield (Ferede et al., 2019; Bekele & Kemal, 2022).

Our research revealed that the utilization of advanced charcoal-making technology kilns significantly improved the efficiency of converting wood into charcoal, with enhancements ranging from 20 to 43% when compared to traditional earth mound kilns. An examination of conversion efficiency results from carbonization tests involving various wood types and kiln designs, including the traditional masonry or earth kilns employed in diverse regions across the globe, highlighted the substantial variability in charcoal yields, typically falling within the range of 20% to 35% by weight (Sparrevik et al., 2015a; Jolien Schure et al., 2019; Nahrul Hayawin & Idris, 2022). A substantial increase in conversion efficiency is highly advantageous for smallholders in the southern Achefer district, as it enables them to obtain greater charcoal yields from the same modest plots of land within the *Eucalyptus camaldulensis* small-scale plantation-based charcoal production system. Enhancing the efficiency of the wood-to-charcoal conversion process also carries the potential to serve a dual purpose: conserving trees and reducing greenhouse gas emissions. By reducing the quantity of dry wood required to produce the same amount of charcoal, more trees and shrubs can remain intact, preserving their stored carbon and thus contributing to climate change mitigation. This is a departure from the scenario when traditional earth mound kilns are employed (J Schure et al., 2021), which typically result in the removal of these trees.

Furthermore, our study's findings indicate that improving wood-to-charcoal conversion efficiency through advanced kilns would facilitate the expansion or afforestation of Eucalyptus plantations on previously degraded lands that had remained devoid of tree cover. Key indicators of the sustainability of Eucalyptus plantation-based charcoal production include the superior benefits offered in comparison to croplands, the practice of rotating Eucalyptus plantations every 5–7 years during harvesting, and the conversion of both fertile and degraded land into afforested Eucalyptus plantations for charcoal production (A. Worku et al., 2021; Tesfaw et al., 2023). These lands, previously unsuitable for crop cultivation due to degradation, could benefit from the introduction of Eucalyptus plantations, which have the potential to mitigate or prevent erosion in such areas. Consequently, enhancing wood-to-charcoal conversion efficiency and reducing emissions will further bolster the sustainability of this practice and promote its expansion onto degraded lands. Given that Eucalyptus plantations may adversely affect groundwater supply in specific regions of West Gojam, it becomes crucial to implement effective management practices, including proper spacing and selecting suitable farming sites.

Conversely, our findings reveal that small-scale charcoal producers in the study area suffer losses ranging from 20 to 43% of their total charcoal production due to the utilization of inefficient traditional earth mound kilns in the South Achefer district, North Western, Ethiopia. Examining the values associated with non-commercial charcoal, the GMDR

Table 2 Mean ± SE values of selected gases 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 ± 22.23^{a}	486.87 ± 11.97^{a}	1.27 ± 0.09^{a}	1.80 ± 0.09^{a}	0.73 ± 0.03^{a}	52.37 ± 1.3^{a}
Casamance	1682.37 ± 11.66^{b}	295.93 ± 8.13^{b}	0.77 ± 0.04^{b}	0.73 ± 0.04^{b}	0.43 ± 0.04^{b}	36.87 ± 0.58^{b}
GMDR	1295.87 ± 13.29^{d}	222.57 ± 5.26^{c}	0.23 ± 0.03^{c}	0.37 ± 0.03^{c}	0.37 ± 0.03^{b}	27.73 ± 0.42^{c}
MRV steel	1541.37 ± 22.75^{c}	265.60 ± 6.26^{b}	0.17 ± 0.03^{c}	0.43 ± 0.03^{c}	0.37 ± 0.03^{b}	32.13 ± 0.57^{6}
P-value	***	***	***	***	***	***
CV	1.7	4.5	13.3	8.1	11.3	3.8

Columns with different letters are significantly different 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; NOx: nitrogen dioxide; SO_2: Sulphur dioxide; and CH_4: methane; ***: $P \leq 0.001$

kiln markedly reduces non-commercial charcoal by approximately 48.7% when compared to the earth mound system (Table 1). This improvement is attributed to the more uniform carbonization process in the advanced kiln in contrast to the traditional earth mound charcoal production method. Observations indicate that approximately 3–5% of the charcoal produced consists of non-commercial charcoal, characterized by very fine particles left over, small fragments, or mixed with soil. This amounts to approximately 176,000 tons of non-commercial charcoal within the total production of 4.4 million tons of charcoal in Ethiopia. There is a need for research investigations to explore the potential utilization of this leftover fine charcoal, referred to as biochar, for soil improvement in Ethiopia. If the charcoal production process is confirmed to be free of organic pollutants, collecting, crushing, and combining biochar with nitrogen fertilizer whether organic or mineral could emerge as a viable method to enhance soil quality. This approach holds promise for increasing soil pH, improving water storage capacity, enhancing nitrogen retention, and contributing to carbon sequestration through the application of biochar fertilizer. Such measures have the potential to enhance the income of charcoal producers.

Conversely, it is worth mentioning that the unburned wood percentage increased by 90% in the GMDR kiln compared to the traditional kiln. Incomplete combustion of wood, leading to a higher proportion of unburned material in the charcoal, may arise from the design conditions of GMR kilns. For instance, an elevation nature of the composition chamber of GMDR kilns by approximately 5–7 cm from the floor could impede the initiation of carbonization for the dry wood stacked below this elevated chamber. The combustion chamber is the site of the initial firing, a phase crucial for initiating the carb onization process.The composition chamber influences the efficiency of converting wood into charcoal, thereby impacting the overall carbonization yield (Temmerman et al., 2019).

Gases emission in kilogram per tonne of charcoal produced from Eucalyptus camaldulensis small-scale plantation

An examination of gases emissions data reveals substantial variability across different charcoal-making technology kilns. Notably, a statistically significant difference ($P < 0.001$) was observed in the emissions of selected gases, with the following order: Green mad retort kiln (GMDR) < MRV steel < Casamance < traditional earth mound kilns (Table 2). The lowest carbon dioxide (CO_2) emissions per tonne of charcoal were recorded at the Green mad retort kiln (1295.87), followed by MRV steel (1541.37), and Casamance (1682.37), while the traditional Earth mound kiln exhibited the highest CO_2 emissions (2632.77). Furthermore, the results of a one-way analysis of variance indicate that the emissions of carbon monoxide (CO) and methane (CH_4) in kilograms per tonne of charcoal produced were as follows: Green mad retort (222.57 ± 5.26 and 27.73 ± 0.42), MRV steel (265.60 ± 6.26 and 32.13 ± 0.57), Casamance (295.93 ± 8.13 and 36.87 ± 0.58), and Traditional earth mound kilns (486.87 ± 11.97 and 52.37 ± 1.3). The findings of significant variation in greenhouse gas emissions among different charcoal-making kilns have far-reaching implications for the environment, economics, public health, and sustainability. These results emphasize the importance of adopting more efficient chrcoal kilns and policies to mitigate the environmental impact of charcoal production while promoting sustainable practices in the charcoal industry. The comparative analysis of different kilns and their emissions can also provides valuable information for stakeholders in the charcoal production industry. It allows charcoal producers to make informed decisions regarding technology choices, environmental regulations, and sustainable production practices.

Consistent with these findings, a similar study of improved charcoal-making kilns revealed comparable mean emission factors per tonne of charcoal production as follows: carbon dioxide (CO_2) at 1950 ± 209, carbon monoxide (CO) at 157 ± 64, and methane (CH_4) at 24 ± 17 compared with the emissions from traditional kilns, which recorded CO_2 at 2380 ± 973, CO at 480 ± 141, and CH_4 at 54 ± 29 (Sparrevik et al. 2015b). A separate investigation focusing on charcoal-making kilns frequently employed in Kenya and Brazil similarly revealed a spectrum of emissions for various pollutants per kilogram of charcoal produced. These emissions included carbon dioxide (CO_2) ranging from 543 to 3027 g, methane (CH_4) from 32 to 62 g, carbon monoxide (CO) spanning 143 to 373 g, total non-methane organic compounds varying between 24 and 124 g, nitrous oxide (N_2O) fluctuating from 0.011 to 0.30 g, and nitrogen oxides (NO_x) between 0.0054 and 0.13 g (Pennise et al., 2001).

Similar patterns, with very limited emissions (less than 0.77 kg per tonne of charcoal), were observed for gas concentration–time profiles, including NO, NO_x, and SO_2, across all types of charcoal kilns. This suggests that the carbonization process proceeds uniformly throughout the cross-section of the kilns. Nevertheless, differences were noted in the instantaneous concentration values of emissions measured across all kilns. For instance, there was an increasing trend in the concentration of carbon monoxide (CO) and methane (CH_4) between day two in the case of improved kilns and days two to four for traditional earth mound kilns. This phenomenon was particularly evident in the cases of CO_2 and CO, which are the dominant product species in the carbonization gas. These species exhibited an increase as soon as the levels of N_2 and O_2 began to decrease over the subsequent four days (Charvet et al., 2022).

Moreover, more efficient charcoal kilns results in a substantial reduction in gas emissions, including a decrease in carbon dioxide (CO_2) by 39.2–50.7%, carbon monoxide (CO) by 39.2–54.3%, and methane (CH_4) by 29.6–47%. This study underscores that improved kilns effectively curtail the amount of wood required for charcoal production, achieved through enhanced techniques and the implementation of chimneys. Consequently, these advancements play a pivotal role in mitigating atmospheric pollution by lowering greenhouse gas emissions (Ahmad et al., 2022; Cornelissen et al., 2016; Girard, 2002; Rai et al., 2019; Tippayawong et al., 2019).

Consistent with these findings, the process of charcoal production from *Acacia decurrens* smallholder plantations showcased substantial emissions reductions through the use of improved charcoal making kilns (Tazebew et al., 2023). These reductions ranged from 46% to 57.9% for CO_2, 29.4% to 56.6% for CO, 61.7% to 86.1% for NO, 56.6% to 86.2% for NOx, 41% to 62.8% for SO_2, and 35.7% to 57% for CH_4 (Tazebew et al., 2023). Similarly, other studies have consistently identified the GMDR kiln as one of the cleanest charcoal-making technologies with significantly reduced emissions of methane (M Temmerman, 2016; Temmerman et al., 2019; Tippayawong et al., 2019; Schettini et al., 2022). This advantage is attributed to the combustion of methane within the kiln-furnace system, which not only offers technological benefits but also contributes to a lower environmental impact compared to conventional charcoal production methods (Ribeiro et al., 2020).

Moreover, the study reveals a substantial contrast in greenhouse gas (GHG) emissions, with traditional earth mound kilns registering the highest at 126,482 kg CO_2e yr^{-1}, while GMDR recorded the lowest at 88,848.7 kg CO_2e yr^{-1} (Fig. 5). Consequently, the implementation of enhanced charcoal-making kilns resulted in the avoidance of 11,539 kg of CO_2e yr^{-1} in Casamance and 37,633 kg CO_2e yr^{-1} in GMDR (Fig. 5). This can be attributed to the superior efficiency of wood-to-charcoal conversion in improved charcoal-making kilns, facilitated by controlled airflow mechanisms and an effectively designed system, preventing the release of greenhouse gases during charcoal production (Pennise et al., 2001; Temmerman et al., 2019). These findings

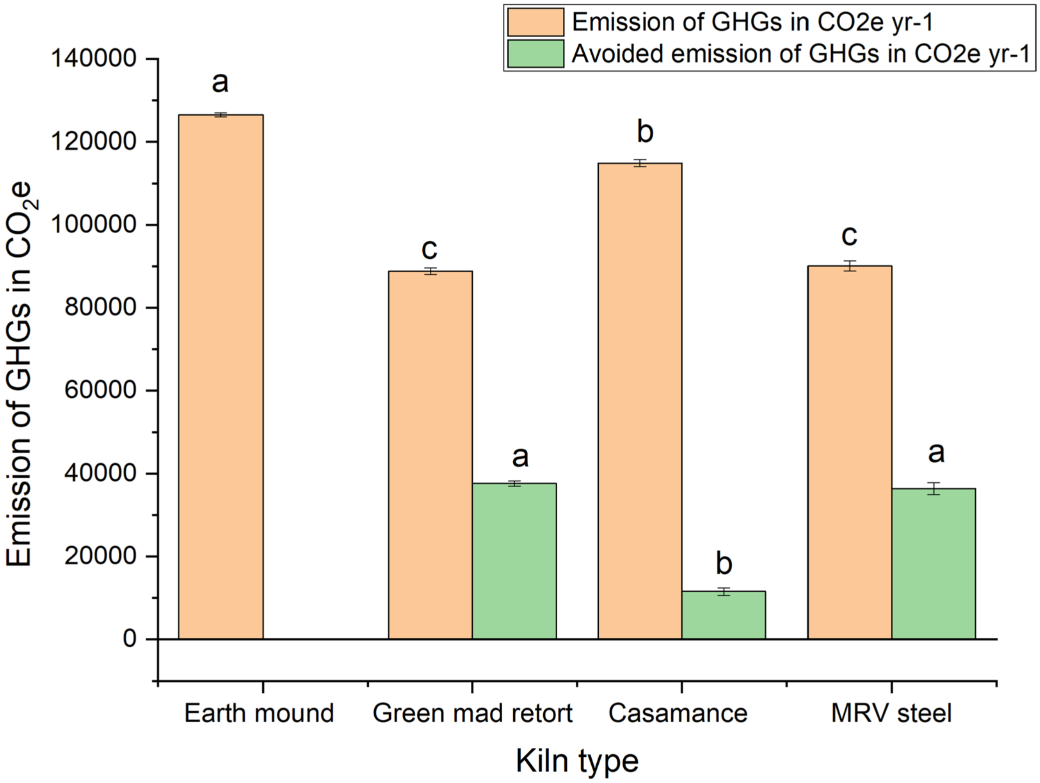
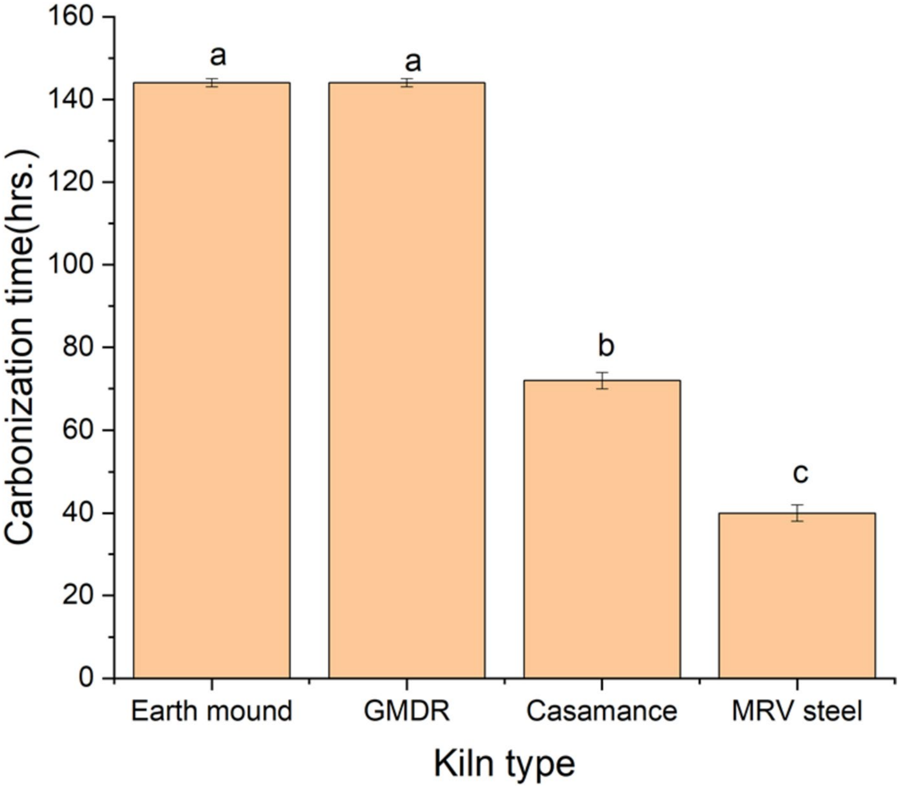


Fig. 5 Emission of GHGs in CO_2e yr^{-1} and avoided emission of GHGs in CO_2e yr^{-1}. Columns with different letters are significantly different at $P < 0.05$. GMDR: Green mad retort kiln, MRV: Mark v kiln, GHGs: Greenhouse gases, CO_2e: Carbon dioxide equivalent, Error bars: mean ± SE

underscore the significant implications of exploring opportunities for carbon credits and securing funding from climate initiatives to facilitate the transition to advanced charcoal-making technology. Based on the current finding encourage and support the widespread adoption of improved charcoal-making kilns, as they have been demonstrated to significantly reduce emissions. This can be achieved through financial incentives, technology transfer, and capacity building for charcoal producers. Furthermore, invest in research and development to further enhance the efficiency and environmental performance of charcoal-making kilns. Continuous innovation in this sector can lead to even more significant emissions reductions.The environmental impact of carbonization gases, such as CO, presents a serious health hazard to local communities and has significant consequences for the environment, as well as broader natural resource management practices (M Rai et al., 2019; Temmerman, 2016). The implications of this research are significant, as they shed light on the critical environmental and health impacts of carbonization gases, particularly carbon monoxide (CO). It highlights the detrimental effects on local communities and the environment, making it imperative to address these issues. Notably, the GMDR improved kiln stands out as having the lowest greenhouse gas emissions due to its innovative approach. This kiln recirculates smoke gases from the carbonization chamber back to the external fire-box, effectively burning a higher proportion of tar components and harnessing the generated heat for further wood-to-charcoal carbonization (Temmerman et al., 2019). Consequently, the adoption of less emissions-intensive charcoal kilns technology could offers the potential to substantially reduce emissions, enabling countries in Sub-Saharan Africa to contribute to the fight against climate change while also accessing a sustainable source of cooking fuel (Temmerman et al., 2019). It is worth noting that the values of greenhouse gas emissions, particularly methane,

Fig. 6 Carbonization time of wood to charcoal conversion 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 ± SE



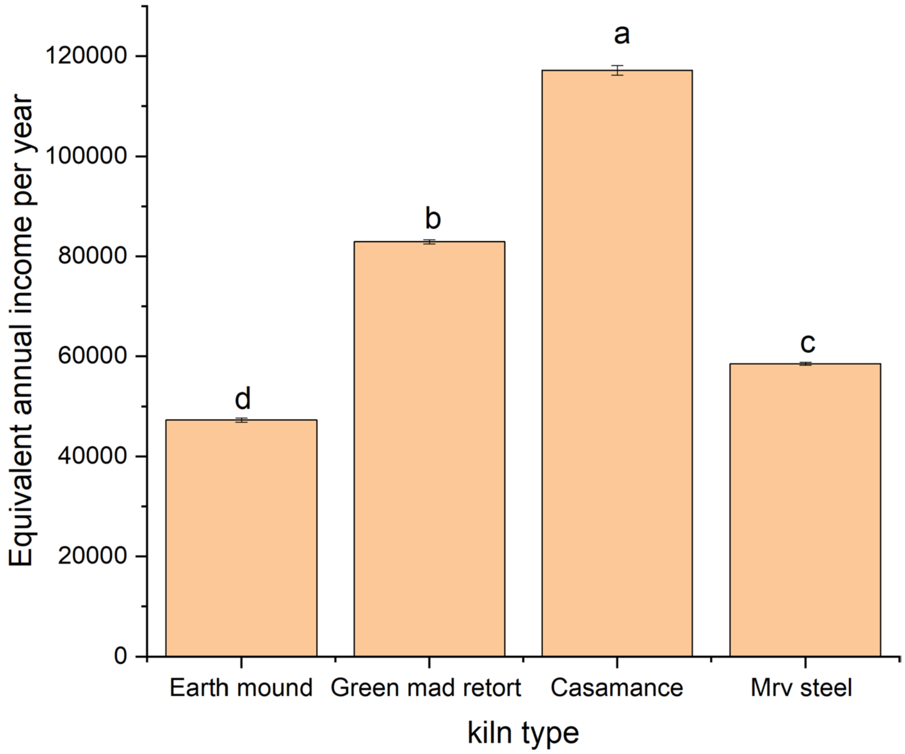
in the current study exceed those observed in a study conducted in Madagascar (Temmerman et al., 2019). This variance in values may be attributed to differences in the characteristics of wood, including diameter and moisture content, as well as variations in the carbonization processes employed during the charcoal-making process (Kammen and Lew, 2005). These differences underscore the importance of tailoring solutions to specific regional contexts.

Carbonization time of wood to charcoal conversion of Eucalyptus camaldulensis dry wood for the different improved charcoal kilns

The GMDR and traditional earth mound kilns demonstrated the lengthiest average carbonization period, lasting 144 h, as evidenced in Fig. 6. Conversely, MRV kilns required the shortest duration, only 40 h, while Casamance kilns needed 72 h to complete the carbonization process. Traditional earth mound kilns, on average, yielded 685.9 kg of charcoal every 6 days. In contrast, Casamance and MRV steel kilns were more efficient, producing 940.83 kg and 808.6 kg of charcoal every 3 and 2 days, respectively. For the GMDR kiln, the cooling phase accounted for the longest duration at 96 h, while effective carbonization was achieved in just 48 h. Other reports from the Namibian Charcoal Association indicate that the charcoal carbonization cycle in traditional kilns lasted approximately 144 h, in contrast to the Green Mad Retort (GMDR) kiln, which achieved effective carbonization in just 24 h (M Temmerman, 2016).

The conversion time from wood to charcoal was reduced by 50% and 72% when using Casamance and Mark V steel kilns, respectively. This reduction aligns with the findings reported by J Schure et al. (2021). The significant difference in carbonization times between kiln types indicates variations in resource utilization. Longer carbonization periods, as observed in traditional earth mound kilns, may lead to less efficient resource use. The frequency of charcoal production is closely linked to carbonization times. Kilns with shorter carbonization durations can produce charcoal more frequently, potentially impacting market supply and income for producers. Also,

Fig. 7 Financial profitability of the different charcoal-making kilns



more frequent charcoal production from kilns with shorter carbonization times may contribute to market stability and meet growing demand. Whereas, longer carbonization times, especially in traditional kilns, demand constant supervision and close attention to ventilation, making the operation more complex and labor-intensive.

Cost–benefit analysis of the different charcoal-making kilns

Enhancing traditional charcoal-making methods through improved kiln technology holds the potential to boost charcoal income derived from Eucalyptus camaldulensis smallholder plantations in the study area. Furthermore, it promises increased efficiency and environmental benefits, as indicated by the data presented in Table 1 and 2, as well as in Figs. 5. Although the installation costs of these improved charcoal kilns surpass those of traditional kilns, their appeal to rural smallholder farmers hinges on their capacity to produce more charcoal per unit of wood. Analyzing the financial profitability of different charcoal-making kilns, as depicted in Fig. 7, reveals that the Casamance improved charcoal-making kiln yields the highest equivalent annual charcoal income (117,126.9 ETB yr^{-1}), followed by the Green Mad Retort (82,893.8 ETB yr^{-1}) and MRV steel kiln (58,495.9 ETB yr^{-1}). Notably, traditional earth mound kilns, with a charcoal income of 47,304.3 ETB yr^{-1}, exhibit the lowest net present value.

The adoption of improved kiln technology has the potential to significantly boost charcoal income for smallholder farmers in the study area. This can have a positive economic impact on these communities. The text emphasizes that the appeal of improved kilns to rural smallholder farmers is contingent on their capacity to produce more charcoal per unit of wood. The financial profitability analysis presented in Fig. 7 demonstrates that certain kilns, like the Casamance kiln, offer higher equivalent annual charcoal income, despite their higher installation costs. Enhanced energy efficiency can increase the biomass available for various other purposes, benefitting a larger proportion of rural households through more effective biomass stoves, as seen in prvous studies (Gebreegziabher et al., 2017; Nigussie et al., 2021; Villamor et al., 2020). It is imperative to address the drawbacks of traditional earth mound kilns, which are widely used in Africa, including poor carbonization, leading to woody biomass loss, diminished earnings for charcoal producers, elevated pollution levels, and increased greenhouse gas emissions (Mugo et al., 2007).

In this section, it is evident that the costs associated with kilns play a significant role in determining the economic advantages of charcoal sales, regardless of the wood-to-charcoal conversion efficiency of each production technique. For instance, the Green Mad Retort (GMDR) demonstrated a higher efficiency (37.7%) compared to Casamance (32.09%). However, despite its lower efficiency, Casamance kiln achieved higher net present values, generating an annual income of 117,126.9 ETB. The Casamance kiln's shorter carbonization time allows for more frequent charcoal production, contributing to its higher net present value. Furthermore, this outcome can be attributed to the variance in kiln costs, with the GMDR costing 48,333 ETB as opposed to the more cost-effective Casamance kiln, which is priced at 15,000 ETB. Moreover, the shorter carbonization time observed with the Casamance improved kiln allowed for more frequent charcoal production throughout the year, surpassing the performance of the other kilns considered in our study, as indicated in studies by (Ribeiro et al., 2020); Schettini et al. (2021).

Both MRV steel and traditional earth mound kilns display consistent trends in terms of efficiency and annual equivalent income. Enhanced charcoal-making kilns demonstrate the ability to produce charcoal at substantially reduced financial and economic costs per unit of wood, resulting in superior financial benefits (Swami, 2009; Schettini et al., 2021). Furthermore, a study conducted by Oliveira et al. (2014) revealed that when producing an equivalent amount of charcoal, the kiln furnace system outperformed the "hot tail" type by consuming 20% less wood. This not only enhanced cash flow and economic performance but also resulted in a remarkable 16.4% increase in profitability.

In our study, we found that apart from the Casamance improved kiln, both MRV steel and Green Mad Retort (GMDR) kilns substantially reduced the costs associated with wood cross-cutting by 50% and 75%, respectively. The reduction in wood cross-cutting costs in the case of the improved kiln was attributed to the practice of cross-cutting wood logs to approximately 1–1.5 m in length, as opposed to the less efficient process of cross-cutting wood to less than 80 cm, which is common with traditional earth mound kilns. Furthermore, our research revealed that the use of teff straw for covering the kiln or mound, which incurs an additional cost, was entirely eliminated with the employment of Green Mad Retort and MRV steel kilns.

Additionally, the incorporation of superimposed metal barrels in improved kilns offered the advantage of collecting wood vinegar, which can be employed for insect pest and crop disease control. However, it's important to note that Green Mad Retort kilns are stationary once constructed, limiting their use to areas with a consistent and permanent supply of *Eucalyptus camaldulensis* dry wood, as observed in the South Achefer district within our study area. The Casamance-improved charcoal kilns are mobile and flexible, making them easily relocatable to different parts of farmland. This flexibility can be beneficial for charcoal producers, allowing for wider applications and adaptability to varying production scenarios. In cases where stationary or fixed dry wood charcoal production sites are suitable, both Green Mad Retort and Casamance kilns can be effectively utilized.

Conclusion

In conclusion, the findings of this study provide strong evidence in favor of adopting improved charcoal-making technology kilns over traditional earth mound kilns. The use of these advanced kilns resulted in a substantial increase in wood-to-charcoal conversion efficiency, ranging from 20 to 43%. This heightened efficiency has the potential to bring about significant economic benefits, as it allows smallholders to achieve higher yields within the Eucalyptus camaldulensis small-scale plantation-based charcoal production system. This not only enhances the financial prospects for individual producers but also has the potential to positively impact the economic well-being of local communities. Furthermore, the replacement of traditional earth mound kilns with improved kilns led to a notable reduction in carbonization time, ranging from 50 to 72%. This reduction translates to increased productivity, as charcoal producers can either complete an additional round of charcoal production or engage in alternative livelihood activities within the same timeframe that would have been required for a single round in a traditional kiln. This efficiency gain is crucial for improving the overall productivity of the charcoal industry.

Additionally, when evaluating the financial profitability of various charcoal-making kilns, Casamance and Green Mad Retort improved kilns emerged as more financially rewarding options in the study area, compared to traditional earth mound kilns. This highlights the economic viability of transitioning to advanced technology. Moreover, the adoption less emissions-intensive charcoal kilns technology contributes to a substantial reduction in greenhouse gas emissions, including carbon dioxide (CO2), carbon monoxide (CO), and Methane (CH4). This less emissions-intensive charcoal production approach aligns with global efforts to combat climate change and protect the environment.

In summary, the results strongly support the extension of Casamance and Green Mad Retort kilns due to their superior wood-to-charcoal conversion efficiency, net present values, and environmental benefits. As such, it is recommended that the government and relevant authorities encourage and support the transition from traditional charcoal-making methods to these sustainable and environmentally friendly improved charcoal-making kilns. This transition can be facilitated through a range of policy measures, incentives, and initiatives, ultimately leading to a more prosperous, sustainable, and less emissions-intensive charcoal production system. It is important to explore the potential for carbon credits and funding from climate initiatives to support the transition to improved charcoal-making technology. This can provide additional financial incentives for producers to switch to more sustainable practices. These measures are expected to attract local charcoal producers toward a renewable and more sustainable improved charcoal production system. Future research could replicate this study in other regions of Ethiopia and beyond to assess the feasibility and impact of transitioning to improved charcoal-making technology on a broader scale. Similarly, investigating the social and economic impacts of transitioning to improved kilns, including how it affects the livelihoods of small-scale charcoal producers, their communities, and the local economy.

Acknowledgements This work is the outcome of the first author’s contributions as part of their Ph.D. research. The authors extend their appreciation to numerous senior experts from various government and non-government organizations. Special thanks are owed to local charcoal producer Tewodros Berihun (Regional Manager, Energy Programme Ethiopia, GIZ), Tefera Adugna (Senior Energy Advisor, Energy Programme Ethiopia, GIZ), Mr. Getahun Zelalem (EFCCC), Miss Samrawit Dereje (AECCA), and Dr. Getachew Eshete (Hawassa University and freelance consultancy) for their invaluable support and collaborative efforts in this specific study.

Author contribution Ewunetu Tazebew, a Ph.D. candidate specializing in forest and livelihood at the University of Gondar in Ethiopia, made significant contributions to the research, which included conceiving and designing the experiments, conducting hands-on experimentation, analyzing data, and providing interpretations, as well as writing the paper. Professor Shinjiro Sato from Soka University in Japan played a pivotal role in shaping the research by contributing to the conceptualization and experiment design, conducting in-depth data analysis and interpretation, and actively participating in the paper-writing process. Solomon Addisu, an associate professor at Bahirdar University, made invaluable contributions to concept development, experiment design, data analysis, interpretation, and paper writing. Eshetu Bekele, an Associate Professor at Adama Science and Technology University, contributed to concept development, experiment design, data analysis, and paper writing. Associate Professor Asmamaw Alemu from the University of Gondar was also highly valuable in the conceptualization, experiment design, data analysis, interpretation, and paper writing. Professor Berhanu Belay from Injibara University, Ethiopia, similarly contributed significantly to concept development, experiment design, evaluation, and paper writing.

Funding This research received financial support from different sources, including the Plankton Eco-engineering for Environmental and Economic Transformation (PLANE3T) project funded by MEXT, Japan, and the Science and Technology Research Partnership for Sustainable Development (SATREPS) with Grant Number JPMJSA2005, specifically the Eco-engineering for Agricultural Revitalization Towards Improvement of Human Nutrition (EARTH) initiative funded by the Japan Science and Technology Agency (JST) and the Japan International Cooperation Agency (JICA). Additionally, partial support for this study was provided by GIZ and UNDP in Ethiopia.

Data availability The datasets produced and analyzed in this study can be obtained from the corresponding author upon a reasonable request.

Code availability Not applicable.

Declarations

Competing interests The authors declare no competing interests.

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.

References

Ababa. (2019). *Best practices on development and utilization of acacia decurrens in fagta lekoma district, Awi Zone*. Amhara Region.

Abate, D., Borges, J. G., Marques, S., & Bushenkov, V. (2022). An Ecological-Economic Approach to Assess Impacts of the Expansion of Eucalyptus Plantations in Agroforest Landscapes of Northern Ethiopia. *Forests, 13*(5), 686.

Abebe, & Endalkachew. (2011). Effect of charcoal production on soil properties in southwestern Ethiopia. *Middle East Journal of Scientific Research, 9*(6), 807–813.

Adam, J. C. (2009). Improved and more environmentally friendly charcoal production system using a low-cost retort–kiln (Eco-charcoal). *Renewable Energy, 34*(8), 1923–1925.

Addis, F., Melak, S., Tefera, B., & Kassa, H. (2016). Impacts of smallholder tree plantation in Amhara Region of Ethiopia: the case of Lay Gayint and Fagta Locuma Districts. *Ethiopian Journal of Economics, 25*(1), 35–58.

Ahmad, R., Zhou, Y., Liang, C., Li, G., Zhao, N., Abbas, A., Fan, Y., Li, L., Gong, J., Wang, D., Yang, Y., Tang, Z., Sultan, M., Sun, C., & Dong, R. (2022). Comparative evaluation of thermal and emission performances for improved commercial coal-fired stoves in China. *RSC advances, 12*(32), 20886–20896.

Andaregie, A., Worku, A., Astatkie, T., et al. (2020). Analysis of economic efficiency in charcoal production in Northwest Ethiopia: A Cobb-Douglas production frontier approach. *Trees, Forests and People, 2*, 100020.

Baldwin, J., Gellatly, G., Tanguay, M., & Patry, A. (2005). *Estimating depreciation rates for the productivity accounts*. Madrid Spain: Paper presented at the OECD Workshop on Productivity Measurement.

Baumert, S., Luz, A. C., Fisher, J., Vollmer, F., Ryan, C. M., Patenaude, G., Zorrilla-Miras, P., Artur, L., Nhantumbo, I., & Macqueen, D. (2016). Charcoal supply chains from Mabalane to Maputo: Who benefitS? *Energy for Sustainable Development, 33*(129), 138.

Bekele, B., & Kemal, A. W. (2022). Determents of sustainable charcoal production in AWI zone; the case of Fagita Lekoma district Ethiopia. *Heliyon, 8*(12), e11963.

Brobbey, L. K., Pouliot, M., Hansen, C. P., & Kyereh, B. (2019). Factors influencing participation and income from charcoal production and trade in Ghana. *Energy for Sustainable Development, 50*(69), 81.

César, E., & Ekbom, A. (2013). Ethiopia environmental and climate change policy brief. *Sida's helpdesk for environment and climate change*, 1–32.

Charvet, F., Matos, A., Figueiredo da Silva, J., Tarelho, L., Leite, M., Neves, D., et al. (2022). Charcoal Production in Portugal: Operating Conditions and Performance of a Traditional Brick Kiln. *Energies, 15*(13), 4775.

Chidumayo, E. N., & Gumbo, D. J. (2013). The environmental impacts of charcoal production in tropical ecosystems of the world: A synthesis. *Energy for Sustainable Development, 17*(2), 86–94.

Cornelissen, G., Pandit, N. R., Taylor, P., Pandit, B. H., Sparrevik, M., & Schmidt, H. P. (2016). Emissions and char quality of flame-curtain" Kon Tiki" Kilns for Farmer-Scale charcoal/biochar production. *PLoS ONE, 11*(5), e0154617.

Dam. (2017). The charcoal transition: greening the charcoal value chain to mitigate climate change and improve local livelihoods. *The charcoal transition: greening the charcoal value chain to mitigate climate change and improve local livelihoods.*

Dereje. (2019). *Determinants Of Adoption Of Limu Maize Variety In South Achefer District, Amhara Region*. Ethiopi.

Desta, G. D., Abshare, M. W., & Nicolau, M. (2023). Role of Highland-Lowland Linkage as a Coping Strategy for Global Environmental and Socioeconomic Changes: The Case of Southeast Ethiopia. *Mountain Research and Development, 43*(3), R1–R10.

Djampou A., (2019). UNEP Publications: January-June 2019.

Doggart, N., & Meshack, C. (2017). The marginalization of sustainable charcoal production in the policies of a modernizing African nation. *Frontiers in Environmental Science, 5*, 27.

Duguma, L. A. (2013). Financial analysis of agroforestry land uses and its implications for smallholder farmers livelihood improvement in Ethiopia. *Agroforestry Systems, 87*(217), 231.

Endalew, M., Belay, D. G., Tsega, N. T., Aragaw, F. M., Gashaw, M., & Asratie, M. H. (2022). Household Solid Fuel Use and Associated Factors in Ethiopia: A Multilevel Analysis of Data From 2016 Ethiopian Demographic and Health Survey. *Environmental Health Insights, 16*, 11786302221095032.

Ethiopia, F. D. R. O. (2019). *Ethiopia's climate resilient green economy: National adaptation plan*. Federal Democratic Republic of Ethiopia.

Ferede, T., Alemu, A., & Mariam, Y. G. (2019). Growth, productivity and charcoal conversion efficiency of Acacia decurrens Woodlot. *Journal of Academia and Industrial Research (JAIR), 8*(6), 113.

Garrett, H. E., Jose, S., & Gold, M. A. (2000). *North American agroforestry*: American Society of Agronomy, Inc

Gebreegziabher, Z., Van Kooten, G. C., & Van Soest, D. P. (2017). Technological innovation and dispersion: Environmental benefits and the adoption of improved biomass cookstoves in Tigrai, northern Ethiopia. *Energy Economics, 67*(337), 345.

Girard, P. (2002). Charcoal production and use in Africa: What future? *Unasylva, 53*(4), 30–35.

Gizachew, K. (2017). Expansion of eucalypt woodlot and its factors in Cheha District Southern Ethiopia. *World Scientific News, 66*, 163–180.

Guta, D. D. (2014). Effect of fuelwood scarcity and socio-economic factors on household bio-based energy use and energy substitution in rural Ethiopia. *Energy Policy, 75*(217), 227.

Heinze *et al.* (2013). Charcoal production from alternative feedstocks. *Final Report June, 25*, 1–77.

IPCC, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, IGES, Kanagawa Japan.

Kammen, D. M., & Lew, D. J. (2005). Review of Technologies for the Production and Use of Charcoal. *Renewable and appropriate energy laboratory report, 1*.

Kebede, T. A. (2022). Analysis of Factors Affecting Local Household Income Derived from Eucalyptus Woodlot in Jamma District, Ethiopia. *Indonesian Journal of Social and Environmental Issues (IJSEI), 3*(3), 289–299.

Kenne, E. S., Zhang, C., Gan, W., Abban, O., Owusu, E., & Hu, S. (2022). Towards a carbon-neutral environment, the role of biomass energy consumption and trade openness in sub-Saharan Africa: a spatial econometric analysis.

Kerebih, A. (2017). *Technical efficiency of maize production: the case of smallholder farmers in south achefer district of west gojjam zone, amhara national regional state*. Haramaya university.

Kimaryo, B. T., & Ngereza, K. I. (1989). Charcoal production in Tanzania: using improved traditional earth kilns. *Manuscript report/IDRC; 216e*.

Koech, G., Sola, P., Wanjira, E. O., Kirimi, M., Rotich, H., & Njenga, M. (2021). *Charcoal production from invasive Prosopis juliflora in Baringo County, Kenya* (Vol. 4): CIFOR.

Luwaya, E., Chisale, P., Yamba, F., & Malin, M. (2014). *A parametric analysis of conversion efficiency of earthen charcoal making kiln using a numerical method*.

Mabonga-Mwisaka (1983). Charcoal Production in Developing Countries. *Wood-based Energy Production*, 1–29.

Manaye, A., Amaha, S., Gufi, Y., Tesfamariam, B., Worku, A., & Abrha, H. (2022). Fuelwood use and carbon emission reduction of improved biomass cookstoves: evidence from kitchen performance tests in Tigray, Ethiopia. *Energy, Sustainability and Society, 12*(1), 1–9.

Mekonnen, Z., Kassa, H., Lemenh, M., & Campbell, B. (2007). The role and management of eucalyptus in Lode Hetosa district, Central Ethiopia. *Forests, Trees and Livelihoods, 17*(4), 309–323.

Mensah, A. K., & Frimpong, K. A. (2018). Biochar and/or compost applications improve soil properties, growth, and yield of maize grown in acidic rainforest and coastal savannah soils in Ghana. *International journal of agronomy, 2018*.

Molla, G., Addisie, M. B., & Ayele, G. T. (2023). Expansion of Eucalyptus Plantation on Fertile Cultivated Lands in the North-Western Highlands of Ethiopia. *Remote Sensing, 15*(3), 661.

Morgan-Brown, T., & Samweli, B. (2018). A comparison of traditional and improved basic earth charcoal kilns in Kilosa District, Tanzania.

MoWIE. (2010). Report on alternative technologies for improved access to modern rural energy technologies in Ethiopia.

Mugo, F., Nungo, R., Odongo, F., Chavangi, N., & Abaru, M. (2007). An assessment of the energy saving potential and heat loss pattern in fireless cooking for selected commonly foods in Kenya *CARPA Working Paper Series, No. 2*: CAPRA.

Mutimba, S., & Barasa, M. (2005). National charcoal survey: Summary report. *Exploring the potential for a sustainable charcoal industry in Kenya. Nairobi: Energy for Sustainable Development Africa (ESDA)*.

Nacke, J. R. (2021). *Value chain governance in the eucalyptus value chain in Mecha district, Amhara region*. Ethiopia.

Nahrul Hayawin and Idris (2022). Biochar from Oil Palm Biomass. *Biorefinery of Oil Producing Plants for Value-Added Products, 1*, 325-343

Neuberger, I. (2015). *Policy Solutions for Sustainable Charcoal in Sub-Saharan Africa*. The World Future Council: Hamburg, Germany.

Neufeldt, H., Fuller, J., & Langford, K. (2015). *From transition fuel to viable energy source: improving sustainability in the sub-Saharan charcoal sector*: World Agroforestry Centre Nairobi.

Nigussie, Z., Tsunekawa, A., Haregeweyn, N., Tsubo, M., Adgo, E., Ayalew, Z., & Abele, S. (2021). Small-Scale Woodlot Growers' Interest in Participating in Bioenergy Market in Rural Ethiopia. *Environmental Management, 68*(4), 553–565.

Njenga, M., Karanja, N., Munster, C., Iiyama, M., Neufeldt, H., Kithinji, J., & Jamnadass, R. (2013). Charcoal production and strategies to enhance its sustainability in Kenya. *Development in Practice, 23*(3), 359–371.

Ojelel, S., Otiti, T., & Mugisha, S. (2015). Fuel value indices of selected woodfuel species used in Masindi and Nebbi districts of Uganda. *Energy, Sustainability and Society, 5*(1), 6.

Oliveira, A. C., Salles, T. T., Pereira, B. L. C., Carneiro, A. D. C. O., Braga, C. S., & Santos, R. C. (2014). Viabilidade econômica da produção de carvão vegetal em dois sistemas produtivos. *Floresta, 44*(1), 143–152.

Pennise, D. M., Smith, K. R., Kithinji, J. P., Rezende, M. E., Raad, T. J., Zhang, J., & Fan, C. (2001). Emissions of greenhouse gases and other airborne pollutants from charcoal making in Kenya and Brazil. *Journal of Geophysical Research: Atmospheres, 106*(D20), 24143–24155.

Rai, S. M., Brown, B. D., & Ruwanpura, K. N. (2019). SDG 8: Decent work and economic growth–A gendered analysis. *World Development, 113*(368), 380.

Raza, M. A., Khatri, K. L., Memon, M. A., Rafique, K., Haque, M. I. U., & Mirjat, N. H. (2022). Exploitation of Thar coal field for power generation in Pakistan: A way forward to sustainable energy future. *Energy Exploration & Exploitation, 40*(4), 1173–1196.

Ribeiro, G. B. D. D., Carneiro, A. D. C. O., Lana, A. Q., & Valverde, S. R. (2020). Economic viability of four charcoal productive systems from Minas Gerais state. *Revista Árvore, 44*.

Rodrigues, T., & Junior, A. B. (2019). Technological prospecting in the production of charcoal: A patent study. *Renewable and Sustainable Energy Reviews, 111*(170), 183.

Schettini, B. L. S., Jacovine, L. A. G., Torres, C. M. M. E., Carneiro, A. D. C. O., Villanova, P. H., da Rocha, S. J. S. S., & Castro, R. V. O. (2022). Furnace-kiln system: How does the use of new technologies in charcoal production affect the carbon balance? *Industrial Crops and Products, 187*, 115330.

Schettini, B. L. S., Jacovine, L. A. G., Torres, C. M. M. E., Carneiro, A. D. C. O., Villanova, P. H., Rocha, S. J. S. S. D., ... & Castro, R. V. O. (2021). Wood and charcoal production in the kiln-furnace system: How do the costs and revenues variation affect economic feasibility? *Revista Árvore, 45*.

Schure, J., Pinta, F., Cerutti, P. O., & Kasereka-Muvatsi, L. (2019a). Efficiency of charcoal production in Sub-Saharan Africa: Solutions beyond the kiln. *Bois & Forets Des Tropiques, 340*.

Schure, J., Hubert, D., Ducenne, H., Kirimi, M., Awono, A., Mpuruta-Ka-Tito, R., ... & Njenga, M. (2021c). *Carbonization 2.0: How to produce more charcoal with less wood and emissions* (Vol. 1): CIFOR.

Selvakkumaran, S., & Silveira, S. (2019). Exploring synergies between the intended nationally determined contributions and electrification goals of Ethiopia, Kenya and the Democratic Republic of Congo (DRC). *Climate and Development, 11*(5), 401–417.

Smith, H. E., Jones, D., Vollmer, F., Baumert, S., Ryan, C. M., Woollen, E., & Patenaude, G. (2019). Urban energy transitions and rural income generation: Sustainable opportunities for rural development through charcoal production. *World Development, 113*(237), 245.

Sparrevik, M., Adam, C., Martinsen, V., & Cornelissen, G. (2015a). Jubaedah and Cornelissen G. 2015 Emissions of gases and particles from charcoal/biochar production in rural areas using medium-sized traditional and improved'retort'kilns. *Biomass and Bioenergy, 72*, 65–73.

Sparrevik, M., Adam, C., Martinsen, V., & Cornelissen, G. (2015b). Emissions of gases and particles from charcoal/biochar production in rural areas using medium-sized traditional and improved "retort" kilns. *Biomass and Bioenergy, 72*(65), 73.

Swami, S. N., Steiner, C., Teixeira, W. G., & Lehmann, J. (2009). Charcoal making in the Brazilian Amazon: economic aspects of production and carbon conversion efficiencies of kilns. *Amazonian dark earths: Wim Sombroek's vision*, 411–422.

Tadesse, W., Gezahgne, A., Tesema, T., Shibabaw, B., Tefera, B., & Kassa, H. (2019). Plantation forests in Amhara region: challenges and best measures for future improvements. *World Journal of Agricultural Research, 7*(4), 149–157.

Tassie, K., Misganaw, B., Addisu, S., & Tesfaye, E. (2021). Socioeconomic and Environmental Impacts of Charcoal Production Activities of Rural Households in Mecha District Ethiopia. *Advances in Agriculture, 2021*(1), 16.

Tazebew, E., Sato, S., Addisu, S., Bekele, E., Alemu, A., & Belay, B. (2023). Improving traditional charcoal production system for sustainable charcoal income and environmental benefits in highlands of Ethiopia. *Heliyon, 9*(9).

Temmerman, M. (2016). Toward a cleaner charcoal production process. *Small, 2*(3–1), 709.

Temmerman, M., Andrianirina, R., & Richter, F. (2019). Technical and environmental performance of the Green mad retort charcoal-making kiln in Madagascar. *Bois et Forêts des Tropiques, 340*, 43–55.

Tesfaw, A., Senbeta, F., Alemu, D., & Teferi, E. (2021). Value Chain Analysis of Eucalyptus Wood Products in the Blue Nile Highlands of Northwestern Ethiopia. *Sustainability, 13*(22), 12819.

Tesfaw, A., Teferi, E., Senbeta, F., & Alemu, D. (2023). *The spatial distribution and expansion of Eucalyptus in its hotspots: Implications on agricultural landscape*. Heliyon.

Teshome, E., Dereje, M., & Asfaw, Y. (2022). Potentials, challenges and economic contributions of tourism resources in the South Achefer district Ethiopia. *Cogent Social Sciences, 8*(1), 2041290.

Thabane, K. (2020). *Development of charcoal briquettes using Sehalahala (Seriphium plumosum and Felicia filifolia)*. National University of Lesotho.

Tippayawong, K.Y., Santiteerakul, S., Ramingwong, S., Tippayawong, N. (2019) Cost analysis of community scale smokeless charcoal briquette production from agricultural and forest residues. *Energy Procedia, 160*, 310–316.

Usui, T., Konishi, H., Ichikawa, K., Ono, H., Kawabata, H., Pena, F. B., ... & Assis, P. S. (2018). Evaluation of carbonisation gas from coal and woody biomass and reduction rate of carbon composite pellets. *Advances in Materials Science and Engineering, 2018*.

Villamor, G. B., Guta, D. D., & Mirzabaev, A. (2020). Gender specific differences of smallholder farm households perspective of food-energy-land nexus frameworks in Ethiopia. *Frontiers in Sustainable Food Systems, 4*, 491725.

Wartluft, J. L., & White, S. (1984). *Comparing simple charcoal production technologies for the Caribbean*: Volunteers in Technical Assistance Arlington, USA.

Whitman, D. L., & Terry, R. E. (2012). Service Producing Investments *Fundamentals of Engineering Economics and Decision Analysis* (pp. 49–59): Springer.

Woollen, E., Ryan, C. M., Baumert, S., Vollmer, F., Grundy, I., Fisher, J., & Lisboa, S. N. (2016). Charcoal production in the Mopane woodlands of Mozambique: what are the trade-offs with other ecosystem services? *Philosophical Transactions of the Royal Society b: Biological Sciences, 371*(1703), 20150315.

Worku, M. A. (2020). Climate Change Mitigation in Agriculture and Forestry Sectors in Ethiopia: A Review. *Agric. for. J, 4*, 11–18.

Worku, A., Andaregie, A., & Astatkie, T. (2021). Analysis of the Charcoal Market Chain in Northwest Ethiopia. *Small-scale Forestry, 20*(3), 407–424.

Yimer, M. (2016). *The Feasibility of Climate Compatible Development: An Exploration of Ethiopia's Climate-Resilient Green Economy (CRGE) Strategy*. Arba Minch University.

Zorrilla-Miras, P., Mahamane, M., Metzger, M. J., Baumert, S., Vollmer, F., Luz, A. C., Woollen, E., Sitoe, A. A., Patenaude, G., Nhantumbo, I., Ryan, C. M., Paterson, J., Matediane, M. J., Ribeiro, N. S., & Grundy, I. M. (2018). Environmental conservation and social benefits of charcoal production in Mozambique. *Ecological Economics, 144*(100), 111.