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Household level fuelwood use and carbon dioxide emissions in Delanta district, Northeastern Ethiopia

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Introduction: Ethiopian rural households primarily rely on fuelwood as their main energy Q7 source, yet the country lacks precise data on fuelwood harvesting and its economic significance. Consequently, there is limited understanding of CO_2 emissions resulting from fuelwood use.

Methods: This study aimed to estimate the annual amount of fuelwood collected and the associated CO_2 and carbon (C) emissions. Using simple random sampling for household selection, data were analyzed with Excel and Stata.

Results: The results reveal that fuelwood dependency is a major driver of deforestation and CO_2 emissions, with households consuming approximately 2,725 kg of firewood and 26 kg of charcoal annually. Each household also extracts an average of 3,909.3 kg of firewood and 516.5 kg of charcoal annually for sale. Among sampled households, fuelwood constitutes 904,261 kg of energy, with 51% used for household consumption and 96% allocated for income generation. The inefficient burning of this fuel results in significant emissions, adding 974,000 kg of CO_2 or 265,600 kg of carbon annually to the household carbon footprint. On average, each household emits 7,740 kg of CO_2 and 1,960 kg of carbon per year.

Discussion: The study emphasizes that, while fuelwood plays a critical role in household energy and income, its unsustainable use accelerates emissions and deforestation. To mitigate these effects, the adoption of alternative energy sources like electricity and forest conservation through local plantations is essential for climate resilience.

KEYWORDS

fuelwood, forest, deforestation, household, carbon dioxide, emission

1 Introduction

1.1 Background

The global surge in energy demand, driven by population growth, industrialization, and technological advancements, has strained resources and posed significant economic and environmental challenges (Arnold et al., 2006). Energy is vital for sustaining human life, yet access to affordable and efficient energy sources remains limited, particularly in rural communities (Uhunamure et al., 2017; Chen et al., 2006). Globally, more than 2.5 billion people depend on fuelwood as their primary source for cooking and heating (Uhunamure et al., 2017). In developing nations, fuelwood accounts for 60%–95% of energy consumption, compared to 25%–60% in middle-income nations and less than 5% in developed nations (Mhache, 2007).

Household energy sources vary significantly, with urban areas predominantly using electricity and natural gas, while rural areas rely heavily on biomass, including fuelwood (Apodaca et al., 2017). In Africa, approximately 600 million people lack access to electricity and depend on biomass fuels such as wood and charcoal, particularly in rural regions where modern energy options are scarce (Obrumah et al., 2019). Fuelwood is the primary energy source in these areas due to its affordability and accessibility, while alternatives like solar and LPG remain limited by high costs and supply challenges. Additionally, biofuels such as animal dung and agricultural waste are important energy sources in rural settings (Apodaca et al., 2017; Mhache, 2007). Around 60% of urban populations rely on woody biomass for cooking (Tanaka, 2010), and over 80% of Africa's energy supply is derived from wood-based sources such as firewood and charcoal (Cerutti et al., 2015).

The continued heavy reliance on fuelwood for household cooking, heating, and lighting is driven by its affordability relative to other fuel options (Ebe, 2014; Ebe et al., 2017; Uhunamure et al., 2017). Despite global goals for universal access to clean energy, many developing nations lack modern energy sources (Mboumboue and Njomo, 2016). Patterns of household energy use often reflect economic development and welfare levels, with limited resources frequently allocated to fuelwood over electricity (Dawit Diriba, 2014). In peri-urban and urban areas, rising fuelwood demand has led to overexploitation of rural forests (Arnold et al., 2006).

Accurate data on fuelwood extraction remains scarce, yet it is a crucial resource for household energy, particularly in rural Ethiopia, where open-access forests supply fuelwood for both domestic use and income generation (Alemayehu Zeleke and Motuma Tolera, 2019; Berhanu Niguse et al., 2017). However, reliance on fuelwood significantly contributes to deforestation and CO_2 emissions (Bruce et al., 2000; Démurger and Fournier, 2011). In addition to being an energy source, fuelwood and other forest resources serve as vital income sources for rural communities (Babulo et al., 2008; Baral et al., 2019).

In rural Ethiopia, biomass and electricity are the primary energy sources, but electricity access is limited due to inadequate infrastructure and the abundance of natural forests (Berhanu Niguse et al., 2017). In the Adaba Dodola region, approximately 95% of households depend on fuelwood, consuming an estimated 30,000,000 kg of fuelwood and emitting 2,080 kg of CO_2 per household annually (Alemayehu Zeleke and Motuma Tolera, 2019). Globally, fuelwood and charcoal usage accounts for 1–2.4 Gt of greenhouse gas emissions annually, representing 2%–7% of anthropogenic emissions (Sintayehu, 2024). Inefficient forest management, charcoal production, and wood combustion are major contributors to these emissions, as households often prioritize fuelwood over electricity. This dependency exacerbates environmental degradation and entrenches poverty in communities reliant on forest resources (Démurger and Fournier, 2011). Consequently, the use of fuelwood as an energy source accelerates forest degradation and carbon emissions (Bildirici and Özaksoy, 2016).

Fuelwood usage contributes significantly to global CO_2 emissions, worsening climate change. In Africa, particularly in Ethiopia, these emissions are often unrecorded (Mhache, 2007). Limited data exists on CO_2 emissions from fuelwood use due to inadequate assessment mechanisms for fuelwood collection and its economic implications (Miah et al., 2009). While fuelwood remains indispensable for household energy in Ethiopia, it poses substantial environmental concerns due to its contribution to CO_2 emissions.

Although the use of fuelwood generates carbon emissions during combustion, it is often considered "carbon neutral." This concept suggests that the carbon released during combustion is offset by the carbon absorbed during the growth of trees and plants, leading to a net-zero or near-zero carbon impact. As highlighted by the Enters (1997), this perspective aligns with the broader framework of sustainable forest management and its relevance to climate change mitigation. By examining this dual role of fuelwood, the study seeks to offer nuanced insights into its contributions to household energy needs and carbon emissions, thereby shaping policies and practices for sustainable fuelwood utilization.

Given the implications of fuelwood-related CO_2 emissions, the growing atmospheric carbon buildup presents critical challenges for climate stability. Addressing emissions from biomass burning in rural households is crucial. This study aims to quantify fuelwood collection from dry afro-montane forests and assess its CO_2 emission implications in the Delanta district of Northeastern Ethiopia. Also this study ensures that the revised sections explicitly connect the carbon neutrality concept to the study's objective of supporting sustainable fuelwood practices and informing policy.

The main hypothesis of this study is that annual fuelwood extraction from open-access forests significantly contributes to household energy needs and income, with measurable impacts on carbon (C) and carbon dioxide (CO_2) emissions, playing a pivotal role in local energy reliance and environmental carbon release.

The study aims to provide practical information to help public officials and local communities address environmental degradation related to household energy use and develop future energy strategies. Locally, there is limited data on the amount of fuelwood harvested for household energy and its impact on carbon emissions. This study will provide insights into fuelwood's contribution to household energy and its carbon emission implications, serving as a valuable resource for policymakers and sustainable forest managers in climate change adaptation and mitigation.

The specific objectives of this research are to estimate the annual volume of fuelwood extracted from forests, to assess the contribution of open-access forests to household energy use and income, and to quantify the carbon (C) and carbon dioxide (CO_2) emissions resulting from fuelwood extraction and consumption.

2 Methodology

2.1 Description of the study area

2.1.1 Study area overview

The Delanta District is situated in the South Wollo Zone of the eastern Amhara region in Ethiopia (Figure 1). Geographically, it is bordered by the Wadla and Angot districts to the north, Dawunt to the west, Tenta to the south, and Ambasel to the east, with

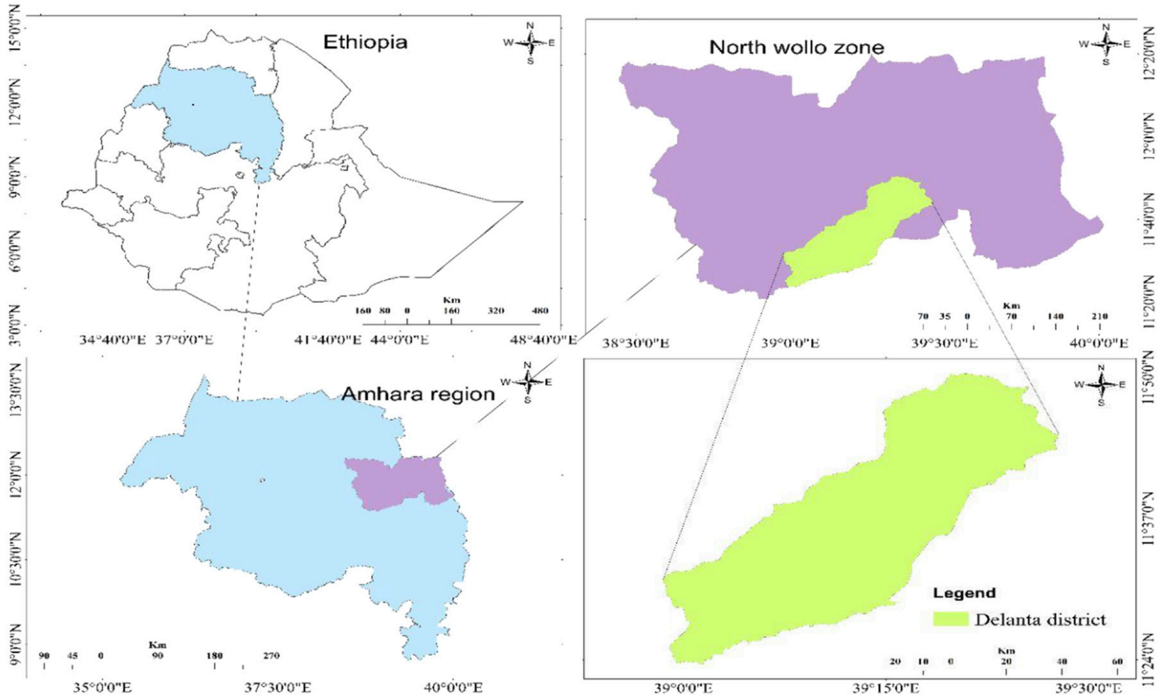

FIGURE 1
Map of study area (source: Authors own work, 2021).

coordinates of 38°40′39″N and 11°20′11″E. The main urban center, Wogeltena, is located approximately 98 km from Dessie, the administrative center of the South Wollo Zone, and 499 km northeast of Addis Ababa.

Historically, Delanta was part of the North Wollo Zone until 2000 E.C. (Ethiopian Calendar), when it was integrated into the South Wollo Zone. Currently, the district is composed of 33 kebeles, including 30 rural and 3 urban kebeles (Delanta District Communication Affairs Office, 2020).

Demographically, the district has a population of 149,882, comprising 72,701 males (50.5%) and 71,181 females (49.5%), as reported by the Central Statistical Agency (CSA) in 2010. Rapid population growth has led to significant challenges, including overcrowding on limited arable land. This has intensified food shortages and resource degradation. Furthermore, the high population density has caused extensive deforestation, habitat degradation, and reduced biodiversity, aggravating the district's environmental issues.

2.1.2 Geographic and climatic characteristics of Delanta district

Delanta District encompasses 106,017 hectares characterized by diverse topography, including 30% plains, 36.5% rugged terrain (gedelama), 30.5% rocky land, and 3.5% mountainous regions. The northern part is predominantly rugged, while the western area features extensive plains. Elevation in the district varies significantly, ranging from 1,900 to 3,800 m above sea level. The Beshilo River serves as a natural boundary with Tenta District before joining the Abay River (Delanta District Communication Affairs Office, 2020).

The district's climate spans multiple agro-climatic zones: 26.4% Dega (moist highland), 41.3% Woyna Dega (midland), 28.5% Kolla (lowland), and 3.8% Wurch (alpine). Annual rainfall fluctuates between 614.8 mm and 968.7 mm, with an average of 803 mm. Rainfall follows a bimodal distribution, with small rains occurring between March and April and main rains falling from June to September. Average temperatures range from 5.9°C to 19.11°C, with maximums varying from 21.2°C to 28°C between January and June, and minimums ranging from 1.6°C to 7.1°C from October to December (Delanta District Communication Affairs Office, 2020).

The soils in Delanta District exhibit favorable characteristics for agriculture but also face certain limitations (Nahusenay Abate et al., 2014). They are primarily heavy clays (35%–80%) with high total porosity (46.51%–60.55%) and low bulk densities (1.02–1.35). Particle densities are within a suitable range (2.41–2.82 g/cm^3), and the soils demonstrate good water-holding capacity (129.9–287.9 mm/m). The pH levels range from 6.25 to 8.29, indicating slight acidity to moderate alkalinity, and the soils are free from salinity (EC < 0.5 dS/m). Organic matter content is low to medium (0.12%–4.82%), and total nitrogen ranges from 0.02% to 0.28%. Available phosphorus shows variability (0.52–18.44 mg/kg). The soils also have high cation exchange capacity (31.98–65.48 cmolc/kg) and base saturation (60.22%–98.97%).

Despite these favorable attributes, the soils are prone to stickiness when wet and hardness when dry, presenting challenges for tillage. Issues such as waterlogging and erosion due to improper land management practices further hinder agricultural productivity. Consequently, effective soil management strategies are essential to enhance the district's agricultural potential and ensure long-term sustainability.

2.1.3 Natural vegetation and energy sources in Delanta district

The distribution of natural vegetation in Delanta District is influenced by factors such as topography, climate, drainage patterns, and soil types. However, high population density and extensive agricultural activities have significantly reduced vegetation cover. The remaining woody vegetation comprises degraded forests, woodlands, scrublands, and scattered trees on farmland. In the northern part of the district, degraded forests have shrunk to less than 1,500 hectares and feature tree species such as Acacia, Juniper, Hygienia, Eucalyptus, and Cordia (Delanta District Communication Affairs Office, 2020).

The district's vegetation includes wooded grasslands, which consist of herbs, grasses, and patches of woody plants. Scrublands are dominated by low shrubs mixed with grasses and herbs, while scattered remnant trees are common across cultivated landscapes.

For energy, traditional biomass, including fuelwood and animal dung, is the primary source for rural and peri-urban households. Access to modern energy sources, particularly electricity, is limited; only 4 rural and 3 urban kebeles out of a total of 33 have electricity. This heavy reliance on traditional biomass highlights the urgent need for alternative energy solutions (Delanta District Communication Affairs Office).

Expanding hydropower-generated electricity to all kebeles is challenging due to the district's rugged topography, which makes distribution to remote areas prohibitively expensive. As a result, firewood extraction and charcoal production from montane forests remain crucial for meeting energy needs and supporting economic activities in the district.

2.2 Sampling technique and sample size

2.2.1 Sampling

The Delanta district was selected for this study as it is identified as one of the areas with significant forest resources within the zone, but also faces considerable forest and land degradation. A multistage sampling procedure was adopted for this research. Initially, out of the 32 total kebeles in the Delanta district, three kebeles were randomly selected: Mesnoamba (01), Goshmeda (019), and Mistinkir (018).

The study respondents comprised rural households that extract fuelwood from the surrounding forest for energy needs. At this stage of sampling, a simple random sampling technique was applied within each selected kebele to determine the total number of household heads to be surveyed. Wealth ranking was not conducted during household selection because the contributions of various income sources and resource endowments to fuelwood dependency vary significantly. Therefore, all individual households within each kebele were randomly chosen for this investigation into the household economy. The total sample size was calculated using the formula provided by Kothari (2004).

Equation 1: sample size determination

$$\mathbf{n} = \frac{\mathbf{Z^2pqN}}{\mathbf{e^2\,(N-1) + Z^2pq}} \tag{1}$$

where: n = the required sample size.

p = 0.1 that is 10%: population reliability (for frequency estimated for a sample size of n)

q = 1−p (1-0.1) = 0.9,

N = 1,452 which is the total number of households in targeted kebeles.

Z = Standard error corresponding to 95% confidence interval which is 1.96, and

e = the margin of error that the researcher tolerates which is (0.05) or the degree of accuracy desired.

So $n = \frac{(1.96)^2*0.1*0.9*1452}{[(0.05)^2*(1452-1)]+[(1.96)^2*0.9*0.1]} = 126$ Households

The required sample of each kebelie could be obtained proportion by using the following formula.

$$nh = \frac{N^*}{Nh}\,(n)$$

where, nh is size of sample each rural kebelie N* = total population of each kebelie to be taken where, as Nh, is size of total population (Kothari, 2004).nh1 (from the 019 kebelie) = $\frac{438}{1452}$ (126) = 38, nh2 (from the 01 kebelie) = $\frac{461}{1452}$ (126) = 40 and nh3 (from the 018 kebelie) = $\frac{553}{1452}$ (126) = 48.

2.2.2 Key informant (KI) selection

In this study, key informants (KIs) were identified as individuals with extensive knowledge of fuelwood extraction from forests, its economic contribution to household economies, and prolonged residency in the community. The selection process employed the snowball method (Bernard, 2002).

During the village reconnaissance, the first farmer encountered was asked to provide the names of potential KIs. From these referrals, one KI was selected per village to represent the study. In total, 12 key informants were selected across all villages. While each individual could provide multiple referrals, only one referral from each pool was recruited, chosen at random.

2.3 Sources of data

To meet the objectives of this study, both primary and secondary data were utilized.

Primary data was gathered through questionnaires, interviews, focus group discussions, and direct measurements.

Secondary data was obtained from books, journals, internet resources, government documents, and communication affairs records from the Delanta district.

2.3.1 Household survey

A structured questionnaire was developed to collect data on available fuel sources. The questionnaire included both close-ended (single-response) and open-ended (multiple-response) questions. Prior to administration, an orientation session was held for randomly selected household heads. The questionnaire, originally prepared in English, was translated into Amharic to ensure respondents' comprehension.

The questionnaire was divided into two main sections:

The first was Household Characteristics: This section captured general demographic and socioeconomic information. And the Domestic Energy Use and Sales: This section explored major fuel sources, distances traveled to collect commercial and non-commercial fuels, and the individual responsible for obtaining each type of fuel.

For traditional fuels, a 1-week reference period was used to minimize recall errors. The survey also examined the reasons for choosing current fuel sources and measured the quantity of each fuel type consumed.

2.3.2 Interviews with key respondents

Structured interviews were conducted with individuals such as development agents (DAs), women, and household heads who actively harvest fuelwood from open-access forests. These interviews aimed to understand participants' insights, feelings, thoughts, and opinions on fuelwood use. A set of structured questions guided the interviews to ensure comprehensive data collection.

2.3.3 Focus group discussion

Focus group discussions (FGDs) were conducted with interested community members in each kebele. The purpose of these discussions was to gather detailed information on household energy use. Participants included representatives from agricultural development agencies, kebele administrative offices, and households that commonly produce charcoal and firewood.

Each FGD involved four households per kebele, and a prepared checklist was used to guide the discussions. The FGDs provided a platform to explore community perspectives on fuelwood consumption and other energy use patterns.

2.4 Methods of data analysis

2.4.1 Household survey data analysis

The data gathered for the study was analyzed using both qualitative and quantitative methods. The quantitative data, obtained from the survey questionnaire and direct measurements, was organized and analyzed through descriptive statistics, such as frequencies, percentages, mean, and standard deviation, to examine various socioeconomic situations.

The qualitative data, collected through personal observations and focus group discussions, was analyzed and described in narrative form by sorting and grouping the views and concepts. The quantitative data was analyzed using MS Excel (2010) and STATA version 14.2.

2.4.2 Fuel measurement proceeding for consumption and sale

Fuelwood consumption measurements were conducted in February, March, and April 2021. A key consideration in these measurements was weighing solid fuels, which enables accurate estimations of consumption (FAO, 2002; Bailis et al., 2015). Weighing was chosen as a more convenient method than measuring volume, as the weight of a bundle of wood, animal dung, or crop residue can be quickly and easily determined using a spring balance. This approach is faster than estimating the gross volume of an irregularly shaped headload of fuelwood, as noted by Broadhead (2016) and Wood and Baldwin (1985).

A total of 126 households were randomly selected for household surveys across three kebeles, representing approximately 10.05% of the total households in the surveyed areas. Over a 1-week period, fuel consumption and sales were measured using a weight-survey method, with the spring balance employed by Ali and Benjaminsen (2004), United Nation Energy Program (2019), and Wangchuk (2011). Prior to this, I completed necessary training in the measurement method for collectors and survey teams.

Fuel types identified by respondents as being used daily (wood, crop residues, dung, charcoal, and kerosene) were physically measured and recorded separately. The estimated daily fuelwood consumption for each household was weighed and provided in bundles or sacks. Respondents were instructed to use only the fuelwood from the weighed bundles and sacks, based on the respective sources of fuelwood (own, forest, or market). On the following day, fuelwood consumption was calculated by subtracting the remaining weight of the fuelwood from the original weight of the bundles or sacks (Miah et al., 2009; World Bank, 2003).

To estimate the daily fuelwood sales per household within the week, respondents were asked to lay out an equivalent amount of fuelwood for the next day's market sale. This identified bundle of wood was measured using the spring balance and recorded. Similarly, other fuels, such as animal dung, were weighed and recorded separately, based on the information provided by the respondents. For households using kerosene, the consumption was measured in liters.

To calculate annual fuelwood consumption, the weight of fuelwood consumed in 1 week was multiplied by 52 (the number of weeks in a year) (Kyaw et al., 2020).

TABLE 1 Parameters used for calculating carbon emission.

Parameter	Value	Source
Annual fuelwood consumed	From household	Weight-survey in HH
Net calorific value fuelwood (wet basis)	15 MJ/KG	IPCC (2006)
Emission factor fuelwood	81.6 CO_2/TJ	UNFCCC (2013)
Conversion CO_2/C	3.667	Ratio molecular weight
Fraction of non-renewable fuelwood	88%	UNFCCC (2013)

Source: UNFCCC (2013).

2.4.3 Estimation of CO_2 emission

Annual carbon emission in the study area was calculated based on clean development mechanism and United Nation framework of Convention on Climate Change (UNFCCC, 2013). Default net calorific values, emission factors and carbon storage in forests. The reason for selecting a climate parameter to assess the effects is required in order to compare and quantify the climatic impacts of different emissions (Table 1).

This methodology, based on the CDM/UNFCCC framework, allows researchers to estimate emissions with minimal data, facilitating wider adoption through tools like online worksheets. While alternative methods, such as direct measurements or region-specific emission factors, could enhance accuracy, they require extensive field data, which was not feasible for this study. The use of internationally accepted default values ensures consistency with global climate mitigation efforts but may not fully capture local variations in fuel quality and practices, introducing some uncertainty. Despite this, the CDM/UNFCCC approach offers broad applicability and comparability, making it a valuable tool for climate impact assessments (Alemayehu Zeleke and Motuma Tolera, 2019).

Equation 2: estimation of carbon dioxide

$$E = FC \times f_{NRB}, \times NCV \times EF - \text{projected} - \text{fossil fuel} \quad (2)$$

where: E, Is emission in kg of carbon dioxide (kg of CO_2)FC, Is the quantity of Fuelwood consumed in kilo gram.f_{NRB}, Is the fraction of non-renewable woody biomass.NCV, Is the net calorific value of fuelwood. EF $_{\text{projected-fossil fuel}}$, default emission factors for all combination of species.

3 Results and discussion

3.1 Household characteristics and fuelwood collection dynamics

The surveyed sample included 126 household heads, with approximately 23.81% of them being female. Respondents' ages ranged from 22 to 85 years, with an average age of 47. Regarding marital status, 66.67% of the household heads were married, 12.70% were widowed, 15.08% were divorced, and 5.56% were single. The average household size was four members, with a minimum of two and a maximum of eight members.

A significant proportion of the respondents, 59.52%, were illiterate, while 18.25% were literate. Additionally, 17.46% of households had some formal education, and 4.76% had attained higher education. Awareness of available services was generally low, with only 36.57% of respondents indicating high awareness, while 26.19% reported low awareness. The remaining 17.46% and 19.84% of respondents had limited or no awareness.

Regarding fuelwood collection, both men and women participate in this activity. Notably, 35% of respondents identified mothers and daughters as the primary gatherers of firewood from forests. In contrast, 32% of respondents indicated that fathers and sons play a central role in producing and transporting charcoal and firewood for cash income. The remaining 33% of respondents acknowledged that both genders contribute to income generation through gathering and selling fuelwood, in addition to fulfilling household energy needs. These findings align with those of Sintayehu and Yemiru (2024), which highlighted women's predominant role in firewood collection.

The demands of fuelwood collection can restrict women's ability to travel long distances, as the activity consumes considerable time and energy, diverting attention from their other household responsibilities. Despite these challenges, women and girls remain essential in making decisions about energy use and managing kitchen activities.

3.2 Major energy sources and status of energy consumption by households

Animal dung and fuelwood are the primary biomass energy sources for households in the Delanta District, with energy obtained from both forested and non-forested areas. The majority of respondents (99%) agree that forests remain their primary source of fuelwood, and they continue to harvest it to varying degrees. This aligns with previous research by Gurmessa (2010) and Aguilar et al. (2015), and Mekonnen and Köhlin (2009), which identified forests as the major fuelwood source in rural Ethiopia. This indicates that fuelwood collection is contributing to forest degradation in the area. Further studies (Berhanu Niguse et al., 2017; Bildirici and Ozaksoy, 2017; Kandel et al., 2016; World Bank, 2003) support this finding and help explain why only a limited amount of fuelwood is collected from non-forest areas, even though woodlots and farm trees do contribute to fuelwood supplies.

In this study area, only 11% of households collect firewood from non-forest areas, while over 70% obtain it from forests. This finding contradicts earlier research suggesting that firewood collected from nearby sources is primarily used as a backup energy source (Kyaw et al., 2020).

As shown in Table 2, among the households that rely on forest resources, 50% use only firewood as their energy source. This is followed by 47.62% of households that use both firewood and charcoal. This pattern is consistent with the findings of Kyaw et al. (2020), who reported that 20% of households in their sample used firewood alongside other energy sources, while approximately 65% (92 households) relied solely on firewood.

Regarding non-forest sources, 42.85% of households depend solely on animal dung for energy, while 38.1% use both animal dung and firewood. When combining fuelwood from both forested and non-forested areas, the remaining small percentage (8%) of households use all forms of energy sources. Only 5.5% of households reported never relying on energy sources other than those from forests.

In conclusion, among the households studied, fuel from forests and dung from non-forests remain the dominant sources of energy, as summarized in Table 2.

3.2.1 Energy sources extracted from forest and other alternatives

The survey revealed that fuelwood, including both firewood and charcoal, is the primary energy source for households, with most of it sourced from open-access natural forests. On average, each household annually extracts 2,725 kg of firewood for personal use and 3,909 kg for sale. This indicates that the volume of firewood collected for income generation significantly exceeds that gathered for household consumption. These findings contrast with Kyaw et al. (2020), who reported average annual *per capita* firewood consumption rates of 298 kg for households relying solely on firewood and 530 kg for those using a mix of firewood and other energy sources. The availability of electricity in the surveyed Myanmar village likely explains this discrepancy.

In total, the households surveyed removed approximately 343,356 kg of firewood annually for personal use and 492,567 kg for commercial purposes. Notably, natural forests contributed 38% of the firewood for household consumption and 55% for sales. Additionally, only 3,260 kg (0.5%) of the total fuelwood extracted was used for household charcoal production, while 65,078 kg (7%) was produced for sale. This resulted in average annual charcoal outputs of 26 kg for household use and 516.5 kg for sale.

Natural forests also provide fuelwood for significant cultural events, such as weddings and funerals (Kandel et al., 2016; Aguilar

TABLE 2 Participant households and available energy sources.

Source of fuels	Energy source	Observation	Participated household N.o	Percent (%)
Forests	Firewood only	126	64	50.8
	Both firewood and charcoal	126	60	47.62
	Charcoal only	126	1	0.8
	None of all fuels	126	1	0.8
Non-forests	Firewood only	126	1	0.8
	charcoal only	126	1	0.8
	Animal dung only	126	54	42.85
	Firewood and charcoal	126	2	1.6
	Firewood and animal dung	126	48	38.10
	Charcoal and dung	126	3	2.4
	All of fuels	126	10	8
	None of all fuels	126	7	5.55

Source: own survey, 2021.

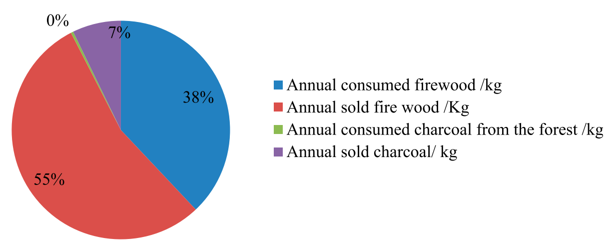

FIGURE 2
Proportional share of fuelwood extracted from forests (source: Authors own work, 2021).

et al., 2015). On average, each household harvested 7,176.7 kg of fuelwood annually, resulting in a total annual extraction of 904,262 kg. This surpasses the average annual harvest of 700 kg reported in community forests in Dolakha, Nepal (Kandel et al., 2016). The data suggests that 66% (557,645 kg) of the fuelwood extracted is intended for sale, highlighting its role as an alternative income source, while only 34% (346,616 kg) is used for household consumption. These findings align with Sintayehu and Yemiru (2024), who observed that, based on the market value of the forest's fuelwood; people depend on it 0.86 times more for income generation than for subsistence needs.

The evidence indicates that more than half of the harvested fuelwood is directed primarily toward financial gain, with charcoal being utilized more for commercial purposes than for household consumption (Figure 2). This suggests that the volume of fuelwood extracted for sale is a significant driver of deforestation compared to that used for personal consumption. Similar studies support this conclusion, indicating substantial annual revenues from fuelwood sales (Sintayehu and Yemiru, 2024). Therefore, it can be concluded that the primary incentive for fuelwood extraction is economic gain, corroborating the findings of Mhache (2007) and Taylor et al. (2014), who emphasize the critical role of fuelwood as an alternative income source.

In addition to forest-derived fuelwood, households in the Delanta district also rely on non-forest fuel sources, such as private trees and animal excrement (Chen et al., 2006). These alternative sources of energy help families meet their fuelwood needs for both domestic use and market sales, particularly when access to forest resources is limited. Rather than actively cutting trees for fuelwood, most households use leftover wood from construction and other activities, as well as by-products from tree management practices like thinning, lopping, and pollarding.

Annually, private trees in the surveyed households produce a total of 47,086 kg of firewood for personal use and 7,618 kg for income generation. On average, each privately owned tree yields 373.7 kg of firewood per year, with 60.5 kg being sold per household. Charcoal production from these trees averages 7.6 kg for personal consumption and 61.5 kg for sale, leading to an annual output of 962 kg and 7,748 kg of charcoal for household use and income generation, respectively. This data underscores the positive impact of encouraging individual tree planting among farmers (Mercer and Soussan, 1992).

In addition to wood-based fuels, households in the region generate an average of 2,303 kg of animal dung annually for personal use and 68 kg for sale. Key informants, development organizations, and community leaders confirmed that families depend on non-forest resources like private trees and animal dung, particularly when forests are too distant to access easily. This observation aligns with findings by Duguma et al. (2014), which showed that rural Ethiopian farmers often use cattle dung as a supplemental energy source due to a shortage of firewood.

As shown in Figure 3, dung constitutes 80% of the energy derived from internal sources, while firewood accounts for only 13%. Sintayehu and Yemiru (2024) also emphasized the significant role of animal dung in subsistence income. Notably, households located farther from forests are more likely to mix firewood with animal dung to meet their energy needs than those residing closer to forest resources. These findings suggest that promoting private tree

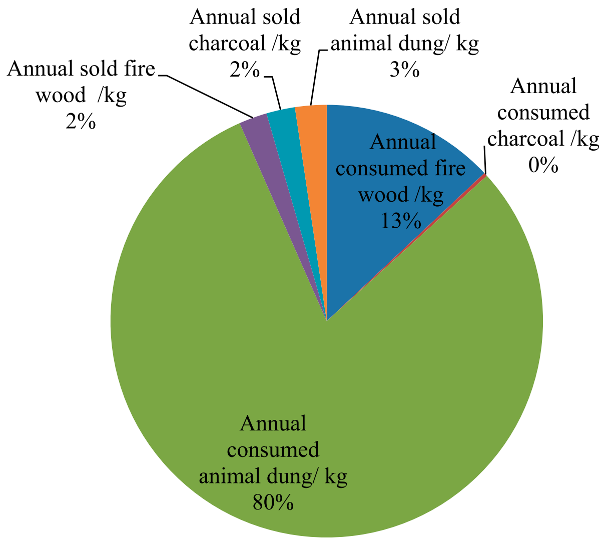

FIGURE 3
Proportional share of energy sources produced from Non-forest sources (source: Authors own work, 2021).

planting could be a sustainable solution to addressing rural fuel shortages (Gebreegziabher, 2007).

3.2.2 Relative contribution of forest fuelwood for household fuel consumption

As previously discussed, the primary energy sources for cooking and heating in the study area are firewood from forests and animal dung from non-forest sources. Among these, firewood remains the dominant energy source. Our findings are consistent with previous studies by Asfaw et al. (2013) and Rahut et al. (2017), which also identified firewood as the main energy source in similar regions. The sampled kebele does not rely on electricity or other modern energy sources.

The survey conducted in this study revealed that, for annual energy consumption, animal dung from non-forest areas accounted for 42% (290,149.6 kg), while firewood from forests made up 50% (343,356 kg). This aligns with the research of Sintayehu and Yemiru (2024), which highlights that, in subsistence economies, firewood from forests represents the most valuable energy source, generating a total of 686,712 Birr annually.

In addition to firewood from forests, households also used fuels like charcoal from the forest (1%, 3,260 kg) and firewood from non-forest areas (7%, 47,086 kg) for cooking and heating. However, according to key informant interviews, households prioritize utilizing trees for constructing homes and generating income from woodlots and home gardens rather than using them for fuelwood (Adanguidi et al., 2020).

On average, each household consumes 2,750 kg of fuelwood from the forest annually, with the total fuelwood consumption for the surveyed households amounting to 346,616.4 kg. This supports findings from Sintayehu and Yemiru (2024), who reported that fuelwood from forests, contributes 23.80% to the income needed for subsistence in a similar region.

In contrast, households use an average of 381 kg of fuelwood from non-forest sources annually, with the total annual consumption reaching 48,048 kg. This figure is comparable to the 2,300 kg of fuelwood consumed per household in Adaba Dodola, as noted in Alemayehu Zeleke and Motuma Tolera (2019) study. However, it is lower than the 6,500 kg of fuelwood consumed per household in Arsi Negele, as reported by Nejib Mohammed (2008). Furthermore, animal dung contributes 290,150 kg annually, making it the second-largest energy source after firewood.

Mekonnen and Köhlin (2009) also found that poorer rural households are more likely to use animal excrement as a cooking fuel. In rural Ethiopia, firewood and charcoal are generally preferred for cooking due to their relative efficiency compared to animal dung. Notably, the majority of crops grown in the study area such as beans, lentils, peas, wheat, barley, and teff are used as livestock feed rather than for energy production. As a result, crop residues are not utilized as a primary energy source. The remaining agricultural residues, mainly from sorghum and maize, are used for thatching traditional homes and as animal fodder, as confirmed by Duguma et al. (2014).

In terms of fuel usage, 98.4% of households in the study area rely on animal dung from non-forest sources, while 90.5% depend on firewood from forests. When measured by weight, forest fuelwood accounts for 51% of the total biomass consumed, with firewood contributing 50% and charcoal 1% (Figure 4). This supports the hypothesis that open-access forests contribute more significantly to household energy consumption than non-forest fuels, including private fuels from farms and other available energy sources. Thus, the alternative hypothesis is accepted.

In conclusion, Ethiopian households currently consume a disproportionate amount of biomass as their primary energy source. This finding is consistent with Maagøe's (2023) review, which notes that 90% of household biomass is used for cooking, with 50%–75% dedicated to preparing Injera using Mitad-style stoves. However, these stoves are highly inefficient, with only 5%–10% of the biomass's calorific content being converted into usable heat. This inefficiency highlights the challenges of fuel-efficient technologies and their contribution to direct greenhouse gas (GHG) emissions.

3.2.3 Relative contribution of forest fuels for sale

Selling fuelwood is a year-round regular activity in Wogeltena town, with the primary source of fuelwood being the nearby open-access natural forest. According to our research, most households in the investigated area continue to rely on forest biomass, particularly fuelwood, as their primary source of income. Additionally, some

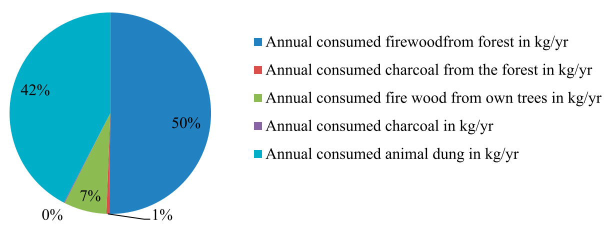

FIGURE 4
Proportional share of energy for consumption from different sources (Source: Authors own work, 2021).

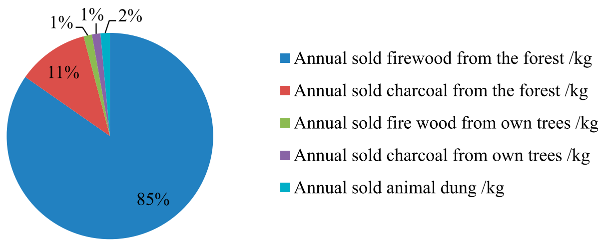

FIGURE 5
Proportional share of energy sources for sale (source: Authors own work, 2021).

households also generate income by selling other biomass-based energy sources.

Similar to the findings of Mhache (2007), our study reveals that fuelwood from the forest accounts for approximately 96% (557,645.4 kg) of the total biomass fuels used to generate cash revenue, while only 4% (23,894 kg) comes from non-forest biomass sources (Figure 5). Mhache (2007) also observed that Tanzanians were primarily motivated to produce fuelwood from forests by the desire to earn money, aligning closely with our findings.

Fuelwood selling in Wogeltena town is a persistent activity throughout the year. Development workers and kebele leaders concluded that impoverished households have limited income sources, and even when they engage in these activities, their earnings remain relatively modest. Consequently, households increasingly depend on the cash generated from selling forest-derived fuelwood. Our survey indicated that low-income households invest significant time in gathering fuelwood to meet both their home energy needs and income requirements. These households often utilize all their collected wood for heating purposes.

Fuelwood from forests in the study area serves as a vital source of employment and income generation. This finding is supported by the study of Sintayehu and Yemiru (2024), which reported that households in their sample earned a total yearly cash income of 985,135 Birr from firewood and 325,390 Birr from charcoal. In the Delanta district, fuelwood from forests contributes 40.65% to the households' relative cash income (Sintayehu and Yemiru, 2024).

Because respondents possessed only large trees on the edges of their croplands, the amount of charcoal produced from private trees was relatively small compared to firewood production. Nearly all charcoal derived from private trees was sold to generate income. However, it was disclosed by primary respondents and development agents (DAs) that most illicit charcoal producer exploit forest resources, treating them as private property for charcoal production. This highlights the prevalence of unauthorized use of forest resources for economic gain.

In conclusion, forest biomass, particularly fuelwood, remains a critical source of income for households in Wogeltena town. While alternative income sources exist, the reliance on forests underscores the urgent need for sustainable management and the development of diverse livelihood strategies to reduce dependence on natural forests for economic sustenance.

3.3 Amount of available energy sources for cash and subsistence use

Figure 6 below illustrates the total annual amounts of available energy sources. Understanding the contribution of each energy source, both for sale and consumption (subsistence), is crucial for calculating the total amounts of energy derived from these sources. According to this assessment, firewood from the forest is the highest biomass energy source, with 492,567.4 kg allocated for sale and 343,356 kg for consumption. The increasing involvement of people in firewood cutting and charcoal production for sale is becoming a significant source of income. Mhache (2014), highlights that this growing demand for firewood from the forest contributes to deforestation.

In addition, among non-forest sources, animal dung used for household purposes has the highest annual amount, totaling 290,150 kg, followed by firewood sold from non-forest sources, which amounts to 47,086 kg. Charcoal production from the forest also ranks high, with an annual amount of 65,078 kg, making it the second-largest forest-based energy source after firewood. This underscores the fact that charcoal is primarily produced for cash generation, which aligns with the findings of Sintayehu and Yemiru (2024) and Atyi et al. (2016), who state that charcoal is mainly produced to generate income. The preference for using charcoal as a source of cash income rather than for subsistence purposes stems from its practical advantages. Charcoal is smokeless, easier to store, and possesses a higher calorific value (30 MJ/kg) compared to firewood (15 MJ/kg). These qualities make it particularly popular in urban and metropolitan areas (World Bank, 2009).

Overall, it can be concluded that a significant portion of energy sources collected for either consumption or sale provides substantial subsistence and cash income. Sintayehu and Yemiru (2024) further emphasize that the forest contributes a total of 703,014 ETB and 1,310,524.8 ETB annually from fuelwood for monetary and subsistence use, respectively. Following this, animal manure (290,149.6 Birr), firewood from non-forest sources (141,258 Birr), and charcoal from the forest (16,302 Birr) also contribute to the overall income. Therefore, fuelwood from the forest remains the dominant source of revenue for both financial and subsistence purposes.

The forest's firewood is the primary source of income for both financial and subsistence needs. Forest fuels are relatively easy to sell due to their quality and efficiency, with the price of energy sources varying according to their specific quality.

The results of this study indicate that fuelwood from the forest represents 71% of the total energy sources accessible to the sampled households, for both consumption and sale. Of this, 66% came from firewood, and 5% from charcoal. This finding aligns with Arnold et al. (2006), who stated that wood collection and extraction for energy purposes account for more than half of the wood removed from forests.

3.4 Estimation of CO_2 and carbon emission

In most nations, the use of fuelwood plays a significant role in environmental degradation (Mhache, 2007). Both the consumption and production of fuelwood negatively impact the environment.

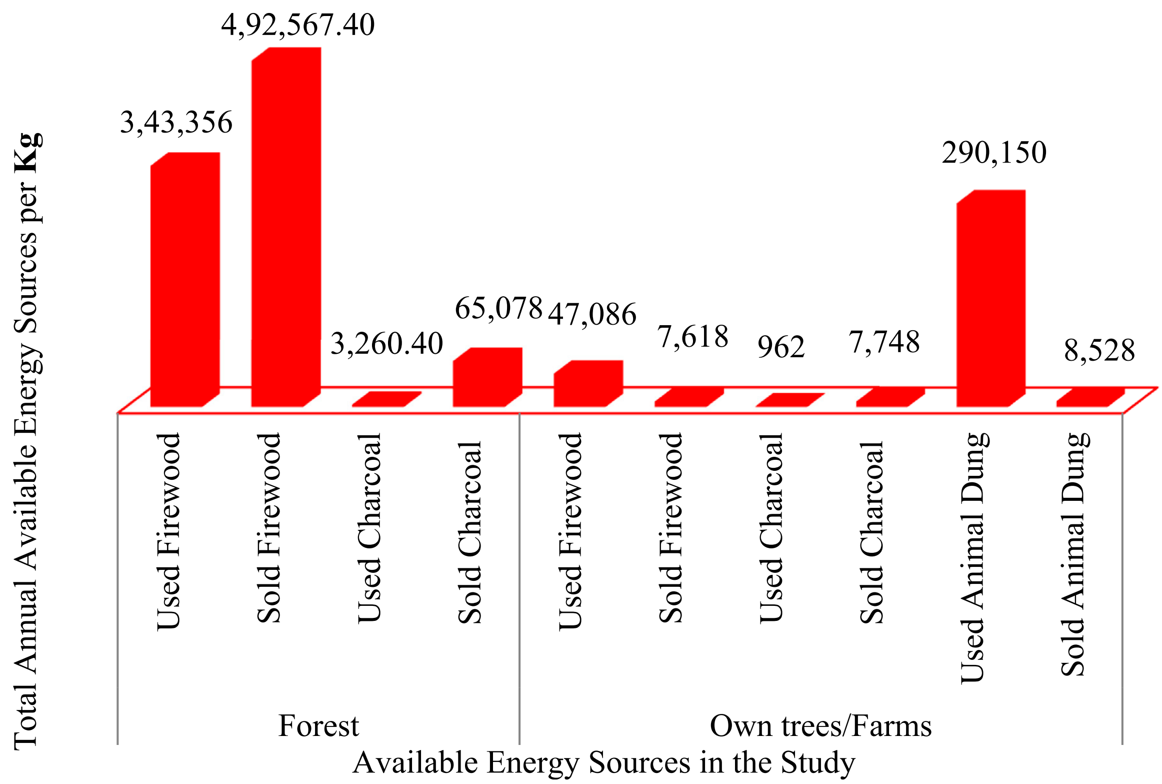

FIGURE 6
Amount of available energy sources for Cash and subsistence use (source: Authors own work, 2021).

Local communities extract various forest resources, such as firewood, charcoal, fodder, lumber, medicinal plants, honey, and fruit, all of which harm the forest ecosystem (Hussain et al., 2019). Furthermore, the inefficient burning of fuelwood using traditional stoves leads to considerable indoor air pollution. For instance, many households still rely on traditional stoves like three-stone fires, which have a thermal efficiency of less than 15% and are fueled by unlimited amounts of firewood.

In this context, we also consider the sale of fuelwood as a source of income for urban populations (Abu-madi and Rayyan, 2013). Maagøe (2023), highlights that land-use changes and greenhouse gas (GHG) emissions are exacerbated when 50% of natural resources are exploited, placing significant pressure on these resources. Additionally, the labor-intensive process of collecting biomass for household use often deprives women and children of time they could otherwise spend on schooling or other income-generating activities.

The study estimated annual carbon emissions using the default net calorific value, emission factors, and carbon storage data from forests. The CO_2 emissions were calculated following the methodology outlined by the Clean Development Mechanism and the United Nations Framework Convention on Climate Change (Bailis et al., 2015; UNFCCC, 2013). It is important to investigate CO_2 emissions from the combustion of solid cooking fuels, particularly in the household sector. Several studies have implicated firewood harvesting and charcoal production in deforestation and forest degradation (Mhache, 2014). However, while these activities undoubtedly have negative impacts, the evidence suggests that the relationship between deforestation and fuelwood demand may be overstated (Adanguidi et al., 2020; Program and Group, 2012).

To assess the contribution of fuelwood to CO_2 emissions, we estimated both the annual fuelwood consumption in the sample households and the amount sold, assuming that all sold fuelwood is eventually consumed. As shown in Table 3, the total annual amount of fuelwood extracted from open-access forests was 904,262 kg. This figure is lower than the prediction by Flammini et al. (2023), who estimated that 741,652 ktons of CO_2 were emitted globally in 2019 due to families using an unsustainable share of fuelwood.

From Table 3, the annual CO_2 emissions amounted to 373,350 kg from household consumption and 600,654 kg from fuelwood sold. The corresponding carbon (C) emissions were 101,813 kg for consumption and 163,800 kg for sale. Therefore, 62% of the CO_2 and C emissions are associated with fuelwood extracted from forests for sale, which serves as an alternative income source. The remaining 38% comes from fuelwood used for household consumption in the study area.

Based on these findings, we accept the alternative hypothesis that fuelwood extracted for sale is a major contributor to CO_2 emissions, surpassing the emissions from fuelwood used for household consumption in the study area.

The results highlight how crucial it is to acknowledge fuelwood's dual contribution to carbon emissions and household energy. The "carbon neutral" label of woody biomass implies that its usage can be sustainable if managed properly, even while combustion contributes to emissions. Promoting techniques like afforestation, reforestation,

TABLE 3 Annual fuelwood produced from the forest.

Variables	Annual consumed firewood	Annual sold firewood	Annual consumed charcoal	Annual sold charcoal	Annual fuelwood
Amount (kg)	343,356	492,567.4	3,260.4	65,078	904,262
CO_2(kg)	369,836	530,554.2	3,511.84	70,096.8	973,998.685
C (kg)	100,855	144,683.45	958	19,115.6	265,611.86

Source: own survey 2021.

TABLE 4 Summary of statistics for fuelwood contribution on CO_2 and C emission.

Variable	Obs	Mean	Std. Dev.	Min	Max
CO_2 of forest fuelwood	126	7,730.147	5,366.054	0	24,644.51
Carbon (C) of forest fuelwood	126	2,108.03	1,463.336	0	6,720.618

Source: own survey 2021.

and better forest management can guarantee a balance between carbon sequestration and release, as the Enters (1997) noted. In order to solve fuelwood shortages and strengthen its role in climate change adaptation and mitigation efforts, policymakers and sustainable forest management must take note of these insights.

$$E = FC \times f_{NRB}, \times N\,CV \times EF_{-projected-fossil\,fuel}$$

The quantity of fuelwood consumed (FC) is 904,262 kg for forests (Table 4). The fraction of non-renewable woody biomass (fNRB) is 88% (0.88). The net calorific value (NCV) of fuelwood is 15 MJ/kg (0.015 TJ/ton). The default emission factor for projected fossil fuel (EF) is 81.6 CO_2/TJ. The CO_2 to carbon conversion factor (CF) is 3.667.

The required calculation for carbon dioxide emissions (E) is:

For fuelwood from the forest, the total CO_2 emission from the sampled households is:

$$904,262\,\text{kg} \times 0.88 \times 0.015\,\text{TJ/kg} \times 81.6\,CO_2/\text{TJ}$$
$$= 974,000\,\text{kg of}\,CO_2$$

In the sampled households, the annual amount of CO_2 emitted due to the consumption of fuelwood extracted from open-access state forests was 974,000 kg. This finding supports the FAO (2007) report, which states that about 18% of global carbon emissions are related to deforestation and land-use change. In a similar study, Abu-madi and Rayyan (2013) estimated that the total annual CO_2 emissions from households in the West Bank amounted to 4.7 million kg. Additionally, Alemayehu Zeleke and Motuma Tolera (2019) found that fuelwood consumption from forests contributed 32,313,000 kg of CO_2 annually, which is considerably higher than our study's estimate.

In another context, Abu-madi and Rayyan (2013) also estimated that the contribution of households' energy consumption in the West Bank to global CO_2 emissions is approximately 0.016%, while the total energy consumption from all sectors accounts for about 0.041%. Specifically, their estimate of CO_2 emissions from fuelwood use was 32,313,000 kg annually, which is roughly equivalent to the deforestation or removal of around 92 hectares of forest. This suggests that fuelwood is one of the most polluting energy sources in terms of CO_2 emissions.

To calculate the carbon emitted, the CO_2 is divided by the conversion factor:

$C = CO_2/3.667 = 974,000\ \text{kg}/3.667 = 265,600$ kg of carbon from forest fuelwood.

In similar study area Sintayehu and Yemiru (2024), studied that Socioeconomic and physical factors near fuelwood users influenced household reliance on forest income. A multiple regression analysis of survey data revealed that factors like age, education, tree ownership, distance to forest and market, and non-forest income negatively impacted fuelwood reliance. The only positive factor was the number of family members.

Table 4 below presents the total and average annual CO_2 and carbon emissions in kilograms.

According to Table 4, above, the average annual amount of CO_2 emitted through fuelwood consumption from forests was 7,730 kg CO_2. The forest contributes high amount of CO_2 than the average carbon dioxide emission estimated by Alemayehu Zeleke and Motuma Tolera (2019), that is 1,300 kg CO_2 emissions. In terms of carbon emissions, it is already estimated that fuelwood combustion extracted from the forest in the sampled households was 265,600 kg. And an average annual amount of carbon emitted from the forest per household is 2,100 kg. The other study also estimates about 8,733,000 kg of carbon with the assumption of a carbon density of 95,000 kg ha^{-1} for dry Afromontane forest in Adaba area was estimated (Alemayehu Zeleke and Motuma Tolera, 2019). The incomplete combustion of the fuelwood has low efficiency. This is resulting in high consumption of fuelwood, which is leading to the more collection of fuelwood from the forests. Furthermore, plantations in rural areas are not sustainable and so are not able to contribute to net carbon sequestration (Miah et al., 2009; Baral et al., 2019).

4 Conclusion and recommendation

This study finds that fuelwood, a key energy source for households in Delanta District, is primarily sourced from open-access natural forests. Annually, an average of 7,180 kg of fuelwood is harvested, making up 51% of total biomass fuel consumption and 96% of biomass fuels used for cash income. The associated CO_2 emissions from fuelwood consumption in the surveyed households reach 974,000 kg, with an additional 265,600 kg of carbon released. Continued forest degradation for fuelwood is likely to accelerate greenhouse gas emissions, exacerbating climate change. A limitation of the research was the inability to quantify CO_2 and carbon emissions from all dead and burned charcoal due to obscured roots. The findings highlight the environmental impact of fuelwood and its significance for household energy, informing policymakers and sustainable forest managers on climate change mitigation.

Recommendations include expanding access to renewable energy sources like hydroelectric, wind, and solar power in the Delanta District, adopting fuel-efficient stoves, and implementing strategies that balance forest conservation with local energy needs. Efforts should focus on increasing agricultural production on cleared lands, promoting agroforestry, and developing alternative energy sources while preserving biodiversity. Establishing protected areas and enforcing laws are essential for effective management, alongside prioritizing fast-growing tree species for fuelwood production and cost-effective projects to maximize global CO_2 savings.

This study emphasizes the importance of community-based sustainable forest management, introducing affordable energy alternatives like solar and biogas, and providing subsidies for renewable energy to lessen fuelwood reliance and CO_2 emissions. Educational initiatives should raise awareness of the environmental impacts of fuelwood use and promote energy efficiency. Encouraging reforestation and agroforestry can restore forest resources, support local economies, and improve carbon sequestration. Policymakers must track CO_2 emissions from fuelwood to set reduction targets, while energy efficiency initiatives can create jobs and minimize environmental harm. Lastly, a strong legal framework is crucial for regulating fuelwood collection, enforcing limits, and imposing penalties for illegal harvesting, ensuring the protection of forest ecosystems. By implementing these strategies, stakeholders can effectively meet immediate energy needs while fostering long-term sustainability and reducing carbon emissions in the Delanta District.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the [patients/ participants OR patients/participants legal guardian/next of kin] was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

AS: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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