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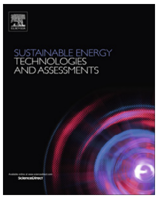

Original article

The carbon footprints of alternative value chains for biomass energy for cooking in Kenya and Tanzania

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ABSTRACT

Due to its availability and affordability for poorer populations, wood-based biomass energy remains vital in meeting local energy demands – especially for cooking fuel – in many regions of the developing world. However, increasing feedstock scarcity (e.g. due to deforestation) coupled with the negative socio-economic and environmental outcomes of inefficient production and consumption technologies make it imperative to identify alternative energy solutions that benefit people without harming the environment. Indeed, tackling energy poverty is crucial to efforts aimed at meeting sustainable development goals at the household level. However, interventions aimed at reducing energy poverty must simultaneously seek solutions that might reduce people's carbon footprint. Carbon footprints, or the amounts of greenhouse gas emissions linked to particular activities, are associated with climate change and its impacts. Globally, calls have intensified to reduce the carbon footprint of energy use, including use of biomass fuels. Locally, climate change issues are increasingly seen as posing particular threats to already vulnerable communities. The present paper evaluates the carbon footprints of alternative biomass energy solutions for cooking, as one key aspect of their environmental performance. It compares the carbon footprints of firewood, charcoal, biogas, jatropha oil, and crop residue briquettes. The research focuses on selected technologies for biomass energy production and consumption in two case study sites in rural and urban contexts of Kenya and Tanzania. Carbon footprinting is applied as a methodological approach to evaluating technological options for sustainable development in developing economies undergoing rapid population growth, urbanization, and industrial development. Results indicate that the unimproved charcoal value chain has a big carbon footprint. The value chain for jatropha oil appears to hold the greatest potential for carbon footprint reductions, as long as the feedstock is grown in the form of hedges around plots. However, the limited yield potential of hedges calls into question the economic viability of this solution. Results further show that carbon footprinting can help to raise awareness and inform stakeholders and decision-makers about alternative, environmentally more suitable biomass energy value chains. However, any assessment of the overall sustainability of these value chains should also integrate socio-economic aspects and factors influencing adoption.

Background and objectives

Biomass energy continues to play a vital role in meeting household energy demands, especially in developing countries, where it remains easily accessible and affordable [1–3]. About 94% of Africa's rural population and 73% of its urban population use wood-based fuels as their primary energy source. Urban dwellers rely heavily on charcoal, while communities in rural areas tend to depend more on firewood [4]. In Kenya, biomass energy covers 69% of the population's overall energy needs, petroleum about 22%, and electricity as little as 9% [5]. In Tanzania, more than 90% of the population depend on wood-based energy for cooking [3,6]. This reliance on biomass energy in its many forms is likely to continue in the foreseeable future, especially in light of population growth, urbanization [2,7,8], and delays in providing access to modern

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energy sources. Only 17% of Kenya's population and 3% of Tanzania's population have access to modern fuels [9].

In both countries, there is growing concern about the negative environmental and socio-economic impacts of this dependence on wood-based energy. Pressure on forests, land and water degradation, greenhouse gas emissions, and adverse effects on human health because of indoor air pollution are the main arguments raised against continued use of wood-based energy carriers. Accordingly, energy policies in Kenya and Tanzania emphasize the need for a shift towards modern energy sources [5]. However, despite widespread views that biomass energy production and consumption technologies are backward, inefficient, and harmful [8,10], alternative biomass energy value chains may still represent viable options capable of simultaneously alleviating poverty through income generation and being environmentally sustainable if properly implemented [11].

Biomass energy can be produced in an environmentally friendly way if raw materials and production technologies are adequately selected [12], and biomass energy supply chains can be sustainable if carbon emissions and economic efficiency are properly addressed [13]. A systematic review conducted by Robledo-Abad et al. [14] indicates that knowledge about the impacts of bioenergy production on sustainable development is primarily concentrated in developed countries. They recommend increasing such knowledge in developing countries. At the same time, assessing the sustainability of biomass energy supply chains is often complicated by data scarcity. Many developing countries lack up-to-date information that can be used in decision-making. For example, up-to-date forest inventories, needed for sustainable wood fuel production, are often unavailable [15].

Increasing feedstock scarcity (e.g. due to deforestation) coupled with the negative socio-economic and environmental outcomes of inefficient production and consumption technologies [8] make it imperative to identify alternative energy solutions that benefit people without harming the environment. One major environmental concern is climate change. Energy use affects the climate by causing emissions of greenhouse gases. The amount of greenhouse gas emissions linked to a particular activity is also referred to as the activity's carbon footprint. Globally calls have intensified to reduce the carbon footprint of energy use, including use of biomass fuels. Locally climate change issues are increasingly seen as posing particular threats to already vulnerable communities. Interventions aimed at reducing energy poverty must therefore simultaneously seek solutions that might reduce the carbon footprint of energy use.

The main objective of the present research is to evaluate the carbon footprints of various biomass energy value chains in two rural and urban contexts in Kenya and Tanzania. We focus on firewood, charcoal, biogas, jatropha oil, and crop residue briquettes, and on selected technologies for the production and consumption of these fuels. We consider biogas, jatropha oil, and crop residue briquettes to be possible alternative energy sources for household cooking. The aim of our research is to help identify less environmentally harmful biomass energy value chains for households that cannot access modern fuels.

Methodology

Study sites

The research was carried out in two case study sites: Kitui County (Kenya) and Moshi (Tanzania). The two sites lie in different agro-ecological zones and provide a good sample of East African ecological conditions. Furthermore, both sites are in the vicinity of medium-sized towns that represent substantial, but still assessable consumer markets for locally produced biomass fuels.

Kitui County in Kenya has a population of about one million [16], 90% of which lives in rural areas. Population growth, estimated at 2.1%, is expected to increase pressure on natural resources [17] and to aggravate land degradation. An estimated 96.9% of people in Kitui County use solid biofuels for cooking [16]. Of these people, 89% use firewood as their main source of energy, while 8% rely mainly on charcoal [18]. Firewood use dominates in rural areas, while charcoal use dominates in urban areas. Nearly 300,000 bags of charcoal are produced in the county annually, causing severe land degradation in an already fragile ecosystem [19].

Moshi, located in Kilimanjaro Region in Tanzania, has a population of about 700,000. Between 2002 and 2012, population growth in Kilimanjaro Region was 1.8%. This is lower than the national average of 2.7% [20], but still high enough to cause increasing pressure on natural resources, including wood for energy production. Similar to Kitui County in Kenya, firewood and charcoal are the dominant sources of energy for cooking for about 90% of rural and urban populations in Moshi [21].

Carbon footprinting

We applied the Life Cycle Assessment (LCA) technique to calculate and compare the carbon footprint of five different biomass energy value chains (see Table 1 and Section "Selected value chains and assumptions"), focusing on selected production and consumption technologies. The international ISO 14040 standard defines LCA as a technique used to quantify the environmental impacts of a product over its whole life cycle, from raw material acquisition through production, use, end of life treatment, recycling, and disposal [22]. It analyses the material flows and energy flows, quantifies environmental impacts, identifies opportunities for environmental improvement, and helps decision-makers understand the sources and sizes of impacts throughout the life cycle. It is used for product development and improvement, strategic planning, public policymaking, and marketing.

Our analysis is based on data from the literature and background data from version 3.1 of the *ecoinvent* database [23]. As the global warming potential is a key indicator from a climate perspective, and as this indicator, in the case of energy use, is also strongly related to energy efficiency and land use change, we decided to focus on calculating the carbon footprint, which is considered a key aspect of a full LCA. The data basis for LCA in East Africa is scarce. To date, bioenergy LCAs have mostly focused on developed countries [14]. For this reason, we calculated feedstock amounts and biomass fuel yields based on the specific technology's efficiency (see Table 1) and data from the literature (biogas). Emission data for the different life cycle stages were obtained from secondary sources and through calculation based on the guidelines for combustion of stationery sources of the Intergovernmental Panel on Climate Change (IPCC) [24], especially where we found no emission data in the literature (see Table 1). An analysis was done for potential environmental impacts using the global warming potential (GWP 100a) indicator for climate change of the IPCC [25], expressed in terms of kilograms of carbon dioxide equivalents, which we refer to as carbon dioxide equivalents (CO_2eq) below. Data were analysed using Simapro software [26].

Selected value chains and assumptions

We evaluated the five biomass fuels in combination with several specific production and consumption technologies, which were selected by stakeholders in participatory workshops in Kitui and Moshi, in June 2014. Participatory selection was done with

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Table 1
Biomass energy value chains, life cycle stages, assumptions, and source of data

Life cycle stages		Biomass energy value chain								
		Unimproved firewood	Improved firewood	Unimproved charcoal	Improved charcoal	Biogas	Jatropha oil, manual press	Jatropha oil, diesel press	Briquettes, manual press	Briquettes, diesel press
Feedstock collection	Feedstock collection assumption	-Unsustainable wood harvesting: no regrowth -Manual harvesting of wood	-Sustainable wood harvesting: regrowth -Manual harvesting of wood	-Unsustainable wood harvesting: no regrowth -Manual harvesting of wood	-Sustainable wood harvesting: regrowth -Manual harvesting of wood	-Cow dung: waste product of cattle keeping -Manual harvesting of cow dung	-Seeds from jatropha hedge -Manual harvesting of jatropha seeds	-Seeds from jatropha hedge -Manual harvesting of jatropha seeds	Maize cobs (Kitui) and rice husks (Moshi): waste product from maize/rice farming and waste paper -Manual collection of crop residues	-Maize cobs (Kitui) and rice husks (Moshi): waste product from maize/rice farming -Manual collection of crop residues
	Ecoinvent process adapted	Roundwood {GLO} |harvest, primary forest|Alloc Rec,U" to represent fuel wood production using IPCC default biomass conversion and expansion factors [27] and wood densities of acacia species. The model assumes that some of the wood extracted is usable but some is left unused (such as the roots, foliage, twigs) which decays and emits carbon dioxide.								
Feedstock processing	Technology	None	None	Basic Earth Kiln (BEK)	Improved basic earth kiln (IBEK)	Plastic & VACVINA bio-digesters	Manual oil press	Diesel-powered oil press	Manual briquette press	Diesel-powered briquette press
	Efficiency			13.1% [28]	20% [29]	75% [30]	60% [31]	80% [31]	100% [PA][1]	100% [PA]
	Emission source/ Ecoinvent name	None	None	[28], [32]		[33]		Diesel burned in diesel electric generating set		Diesel burned in diesel electric generating set
Transport[2]	Transport mode and distance	Rural: None Urban: Bicycle (30 km)	Rural: None Urban: Bicycle (30 km)	Rural: None Urban: Motorcycle (30 km)	Rural: None Urban: Motorcycle (30 km)	None	Rural: None Urban: Motorcycle (30 km)	Rural: None Urban: Motorcycle (30 km)	Rural: None Urban: Motorcycle (30 km)	Rural: None Urban: Motorcycle (30 km)
	Ecoinvent name	Transport, bicycle/AF U		Transport scooter			Transport scooter			
Use[3]	Cooking stove efficiency	Three-stones fire place 12.5% [PA]	Maendeleo: 18% Envirofit: 29.7% Rocket: 28% Kuni Chache: 24% Okoa: 40% [PA & TaTEDO]	Unimproved charcoal stove: 24% [34]	Kenya Ceramic Jiko (KCJ): 32% [34] Sazawa: 44% [TaTEDO]	Biogas burner: 55% [33]	Jatropha oil stove: 39.5% [PA]		Briquette stove: 32% (adopted efficiency of KCJ)	
	Lifespan (years)	1 year (where clay bricks are used, as is the practice)	Maendeleo (4.5) Envirofit (5.5) Rocket (5) Kuni Chache (2) Okoa (8)	1.5	3	10	25		3	
	Fuel energy content (MJ/kg)	18		28		17.71	39.8		Maize cob briquette: 17.65 Rice husk briquette: 18.15	

(*continued on next page*)

Table 1 (*continued*)

Life cycle stages		Biomass energy value chain								
		Unimproved firewood	Improved firewood	Unimproved charcoal	Improved charcoal	Biogas	Jatropha oil, manual press	Jatropha oil, diesel press	Briquettes, manual press	Briquettes, diesel press
	Sources of emission data	Calculation using IPCC default emission factors [24] and stove specific fuel consumption [35]–[38]		[28], [34], [37]		[33], [39]	Calculation using IPCC default emission factors [24] and stove specific fuel consumption			
Functional unit		1 MJ	1 MJ	1 MJ	1 MJ	1 MJ	1 MJ	1 MJ	1 MJ	1 MJ

[1] Practical Action (PA) and TaTEDO are two key organizations addressing renewable energy issues in Kenya and Tanzania.
[2] Losses during transport of 5% of charcoal and briquettes and 1% of methane were factored in.
[3] The specific fuel consumption of cooking devices was calculated based on their thermal efficiency, their assumed active lifespan (hours), and the fuel's energy content.

the aim of including the technologies that were deemed most promising in the two research sites. Given our focus on energy for cooking in rural and urban contexts, we adjusted the system boundaries to each type of context: For rural contexts, analysis includes feedstock collection, feedstock processing, and consumption or use, whereas transport is excluded, as it is assumed that households produce their own biomass energy. For urban contexts, analysis includes feedstock collection, processing, transport, and consumption or use. Since biogas is produced and consumed on-site and this is not feasible in cities, the analysis of biogas is restricted to rural contexts. The functional unit applied for the biomass energy value chains is 1 MJ of heat delivered to the cooking pot. If not stated otherwise, the carbon footprinting results are given in reference to this functional unit, i.e. in $kgCO_2eq/MJ$ of heat delivered to the cooking pot. We made specific assumptions for each of the described value chains (see Table 1).

Firewood

Firewood is wood used directly for cooking, without any conversion. Therefore, only consumption technologies were considered in our analysis. The unimproved value chain was assumed to involve indiscriminate harvesting of trees for firewood, without replanting i.e. regrowth, and use of a three-stone fireplace of very low thermal efficiency. Without the replanting of trees, the biogenic carbon dioxide emissions associated with the combustion of wood in this value chain is assessed with the same global warming potential as that of carbon dioxide from fossil sources. This represents the reality of illegal logging for firewood extraction, which leads to overexploitation of forest resources and their degradation.

The improved value chain, by contrast, was assumed to comprise sustainable wood harvesting practices, allowing for regrowth and replanting of trees, and use of an improved firewood cooking stove (Photo 1). However, even when replanting trees immediately after harvesting, it takes an entire rotation period until the biogenic emissions of carbon dioxide are re-accumulated. In order to account for the temporary increase in atmospheric carbon dioxide concentration, we consider biogenic carbon dioxide emissions associated with the combustion of wood according to the accounting method of Cherubini et al. [40]. Assuming a mean time of roughly 44 years, biogenic carbon dioxide emissions are accounted for with a characterisation factor of 0.18 which is approximately a sixth of the global warming potential of carbon dioxide from fossil sources [40].

Charcoal

Carbonization of wood yields a solid residue known as charcoal. The unimproved value chain was assumed to consist of unsustainable wood harvesting practices, use of a basic earth kiln, and use of an unimproved (metal) charcoal stove. Given the unsustainable wood harvesting practices that do not allow for tree regrowth, the combustion of wood in this value chain was considered a fossil source of carbon dioxide. The assumptions made for this value chain reflect the reality of illegal logging for charcoal making, which leads to overexploitation of forest resources and their degradation. For the improved value chain, we assumed use of sustainably harvested wood (parallel harvesting and planting of wood to avoid overexploitation of forest resources), use of an improved basic earth kiln, and use of an improved charcoal stove (Photo 2). Based on these assumptions, the emissions of biogenic carbon dioxide associated with the combustion of wood in the improved value chain was considered, once again according to the recommendations of Cherubini et al. [40] i.e. with a global warming potential of 0.18.

It is worth noting that in the cases of firewood and charcoal, our assumptions cover the widest possible ranges of carbon footprints, with the unimproved value chains representing worst-case

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Photo 1. Firewood stoves. Top (from left to right): three-stone fireplace, *Maendeleo*, *Rocket*; bottom (from left to right): *Envirofit*, *Kuni Chache*, and *Okoa.*

Photo 2. From left to right: unimproved charcoal stove, Kenya Ceramic Jiko (KCJ), and *Sazawa* charcoal stove.

scenarios and the improved value chains representing best-case scenarios (considering the most efficient technologies currently available in the case study sites). Examination of the worst-case scenario helps identify leverage points for improving the various stages of the value chain in question.

Biogas

Anaerobic digestion of organic matter produces biogas: a mixture of methane (CH_4) and carbon dioxide (CO_2). The selection of biogas for this study is based on its potential to provide an alternative source of energy using locally available organic matter otherwise often treated as waste. The environmental burdens related to cow dung used for biogas production are allocated to livestock keeping and not to biogas production. We selected cow dung as the organic matter used for on-site production of biogas because it is readily available in most rural households. Small-scale farmers often collect cow dung and use it as fertilizer. Biogas production is a multi-output process resulting in biogas and digestate. The digestate can be spread on the fields to improve soil fertility. Therefore, we assumed that the use of cow dung for biogas production does not deprive small-scale farmers of its soil-improving functions. The technologies selected include the plastic bio-digester (Kitui) and the VACVINA (Vietnam Gardening Association) bio-digester (Moshi), as well as the biogas burner (Photo 3).

Jatropha oil

Jatropha oil is a plant-based biofuel obtained by pressing dry *Jatropha curcas* (jatropha) seeds and filtering the oil used for cooking in a biofuel stove; jatropha oil stove. Jatropha is a shrub known as an energy crop with promising benefits, including improvement of energy security and reduction of greenhouse gas emissions [41]. In Africa, jatropha is considered one of the most viable candidates for commercial biofuel production, mostly due to its adaptability to semi-arid lands [42], [43]. We assumed jatropha hedges to be the only acceptable source of seeds because they do not compete with food crops for agricultural land [44]. In addition, cultivation of jatropha hedges does not require application of fertilizers, herbicides, or irrigation water. Maintenance of hedges entails minimal labour requirements compared to the drying, husking, and pressing of seeds with a manual oil press. Limiting our analysis to jatropha hedges – and thus excluding plot-based jatropha cropping was crucial to rule out negative effects on food security.

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Photo 3. From left to right: VACVINA and plastic bio-digesters, biogas burner.

Photo 4. Briquette stove.

Briquettes

Briquettes are made by compacting raw organic matter into moulds of shapes and sizes suited for use in a briquette stove (Photo 4). Crop residues are among the materials that can be converted to fuel to provide an alternative renewable source of energy for households. Crop residues can be used as fodder for livestock, as mulching material to increase soil moisture retention capacity, and as compost to improve soil fertility. In our analysis we assume that crop residues are in sufficient supply such that using them as a fuel does not deprive people of their other functions. For the analysis we selected maize cobs, which are available in Kitui, and rice husks, which are available in Moshi, and considered both as waste. Since they are considered waste material, the environmental burdens related to crop residues used for briquette production are allocated to crop farming and not to briquette production. In the case of the manual press value chain we assumed use of waste paper as a binder material, whereas we excluded the use of starch, which mainly originates from food crops, to avoid a trade-off between energy and food security. Briquette making using a diesel-powered press does not require any binder material, as the process generates sufficiently high temperatures to bind the crop residues.

Results and discussion

Carbon footprints of biomass energy value chains

Feedstock collection

Wood harvesting contributes significantly to the carbon footprints of firewood and charcoal value chains. The unsustainable wood harvesting practices that characterize the unimproved firewood and charcoal value chains produce the highest carbon footprints: 0.35 CO_2eq and 0.94 CO_2eq respectively. Even though sustainable harvesting practices reduce the carbon footprint of wood harvesting in the improved firewood value chain to 0.03 CO_2eq (Kitui) and 0.02 CO_2eq (Moshi), this is still higher than the footprint of non-wood-based value chains. The same holds true for the improved charcoal value chain, where wood harvesting has a carbon footprint of 0.08 CO_2eq (Kitui) and 0.06 CO_2eq (Moshi).

According to charcoal producers in the two study sites, charcoal is often made from indigenous tree species that yield a dense, slow-burning charcoal (referred to as “heavy charcoal”). These species are slow-growing and thus highly vulnerable to overexploitation [45]. Their reestablishment in the two study sites mainly depends on natural regeneration, and the continuous harvesting does not allow time for regrowth. Research results indicate that current wood harvesting practices might lead to overexploitation of forest resources and, consequently, to an increase in the amount of carbon dioxide released into the atmosphere [37]. Only sustainable wood harvesting practices enable carbon dioxide released during combustion to be reabsorbed by growing biomass.

Since the environmental burdens related to cow dung used for biogas production and crop residues used for briquettes production are allocated to livestock keeping and crop farming respectively, their feedstock collection phase are thus considered free of environmental burdens. Similarly, feedstock collection phase of the jatropha oil value chain is considered free of environmental burdens since the cultivation of jatropha hedges does not require application of fertilizers, herbicides, or irrigation water, and does not compete with food crops for agricultural land. In addition, all three feedstock types are collected manually.

Feedstock processing

Feedstock processing does not occur in the firewood value chains, since the resource is used without transformation after manual harvesting. The unimproved charcoal value chain includes wood processing using a basic earth kiln that has a carbon footprint of 0.50 CO_2eq, which is 24% and 45% larger than that of an improved basic earth kiln in Kitui (0.38 CO_2eq) and Moshi (0.28 CO_2eq), respectively. The difference between Kitui and Moshi is due to the different thermal efficiencies of the improved charcoal stoves used in either place, which, in turn, gives rise to a difference in the relative importance (i.e. contribution to overall carbon footprint) of upstream activities such as processing.

In rural contexts, biogas production using the plastic digester has a carbon footprint of 7.8E−07 CO_2eq while that of the VACVINA digester is 9.83E−07 CO_2eq.

In rural and urban contexts, jatropha oil production using a manual press has a carbon footprint (1.3E−04 CO_2eq). It is 79% smaller than that of briquette production using a manual press

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(6.3E−04 CO_2eq) and 99% smaller than that of jatropha oil production using a diesel-powered press (2.2E−02 CO_2eq).

Transportation

Transportation of firewood from rural areas to nearby urban areas is usually done by bicycle. The impact of this mode of transportation is considerably lower than that of motorcycles, but the impact of biomass fuel transportation in general is less important than that of other stages in the life cycle of biomass fuel.

Consumption

In rural and urban contexts, use of an improved stove reduces the carbon footprint of firewood combustion from 0.10 CO_2eq to 0.02 CO_2eq (Rocket) and 0.01 CO_2eq/MJ (*maendeleo, kuni chache, envirofit* and *okoa*). Similarly, use of an improved stove reduces the carbon footprint of charcoal combustion from 0.70 CO_2eq to 0.11 CO_2eq (Kenya Ceramic Jiko) and 0.08 CO_2eq (*Sazawa).* Combustion of jatropha oil has a carbon footprint of only 0.01 CO_2eq. Improved cooking technologies with higher thermal efficiencies, such as the ones listed above, lead to reductions in wood consumption and demand for wood resources. Cooking with plant oils, such as jatropha oil, rather than solid biomass fuels offers significant health benefits because of greatly reduced emissions of carbon monoxide and microparticles.

The carbon footprint of biogas combustion in rural contexts is 33% larger than that of unimproved firewood combustion and 87% larger than that of crop residue briquette combustion. However, it is also 78% lower than that of burning charcoal in unimproved charcoal stoves. The overall performance of biogas stoves depends on the adequacy of the primary air inlet during combustion [46]. If too little primary air is added to the mixture, the biogas does not burn fully and part of it escapes unused. Such leakage of methane (CH_4) from biogas systems has a high global warming potential, as CH_4 is a very potent greenhouse gas [33].

Combustion of briquettes in rural and urban contexts has a carbon footprint of 0.02 CO_2eq, which is a reduction by 80% compared to the combustion of firewood using an unimproved stove. However, it is double the size of the footprint of firewood combustion using an improved stove, such as *Envirofit*, *Maendeleo*, *Kuni Chache*, and *Okoa*. Briquettes produced from raw materials that would otherwise have no other use – such as bagasse, coffee, and maize residues or sawdust – provide a more sustainable alternative to unimproved firewood and charcoal [47].

Overall carbon footprint of selected biomass energy value chains

The unimproved charcoal value chain has the largest carbon footprint (2.15 CO_2eq) in both Kitui and Moshi, while the jatropha oil value chain using a manual press has the smallest one (0.01 CO_2eq).

Improved firewood value chains have the potential to greatly reduce the carbon footprint of cooking with firewood, from 0.45 CO_2eq in unimproved firewood value chains to 0.03 CO_2eq (Figs. 1 and 2). At the same time, they can reduce wood demand

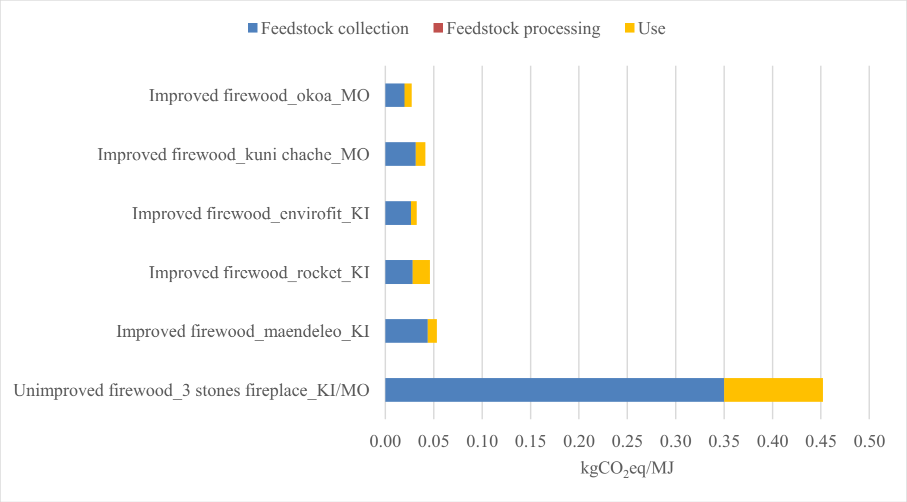

Fig. 1. Carbon footprints (kgCO_2eq/MJ) of unimproved and improved firewood value chains in rural contexts in Kitui (KI) and Moshi (MO).

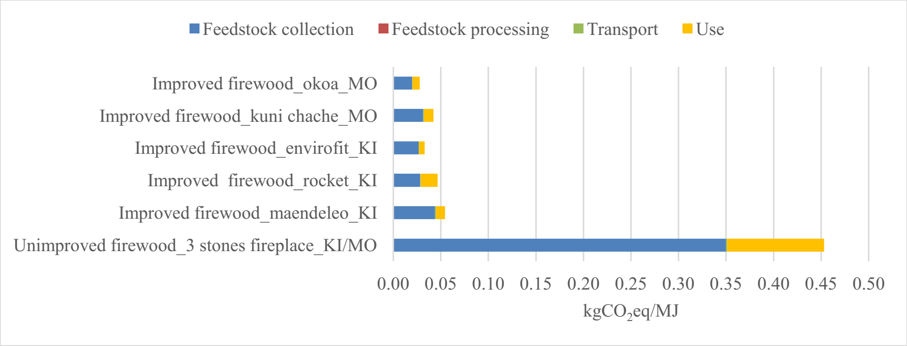

Fig. 2. Carbon footprints (kgCO2eq/MJ) of unimproved and improved firewood value chains in urban contexts in Kitui (KI) and Moshi (MO).

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by up to 57% in Kitui and 69% in Moshi compared to unimproved firewood value chains which result from the combined improvement of better efficiency and reforestation. Figs. 3 and 4 also show that the feedstock collection stage contributes more heavily to the carbon footprint (roughly 60%–80%) than the utilization stage, which only contributes 20%–40%.

The improved charcoal value chain shrinks the carbon footprint of charcoal by about 74% (Kitui) and 81% (Moshi) (Figs. 3 and 4) in both rural and urban contexts compared to the unimproved charcoal value chain. In addition, the improved charcoal value chain reduces the demand on wood resources by up to 54% and 67% in Kitui and Moshi, respectively. Figs. 3 and 4 also show that the carbon footprint of the feedstock processing stage is not reduced much in the improved value chains, as opposed to the feedstock collection and utilization stages, which have a much higher potential for improvement. This means that almost all gains in terms of carbon footprint can be achieved at these two stages. The contribution of transport to the carbon footprint of charcoal value chains in urban contexts is of little significance as compared to the other stages.

Methane emissions significantly contribute to biogas value chains having a large carbon footprint (Fig. 5), making biogas the least suitable among the alternative biomass energy value chains available in the study sites. The reduction of methane emissions largely depends on the degree of organic matter degradation in the substrate and on the retention time of the substrate in the digester; the longer the retention time, the less methane is emitted. This makes methane emissions difficult to control. Defaults between the digester and the biogas burner may cause additional methane emissions.

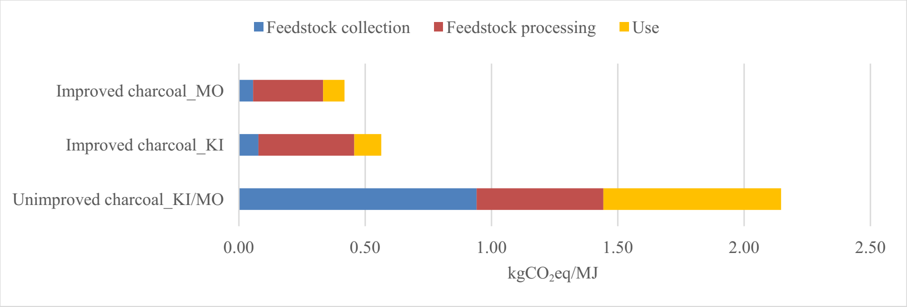

Fig. 3. Carbon footprints (kgCO$_2$eq/MJ) of unimproved and improved charcoal value chains in rural contexts in Kitui (KI) and Moshi (MO).

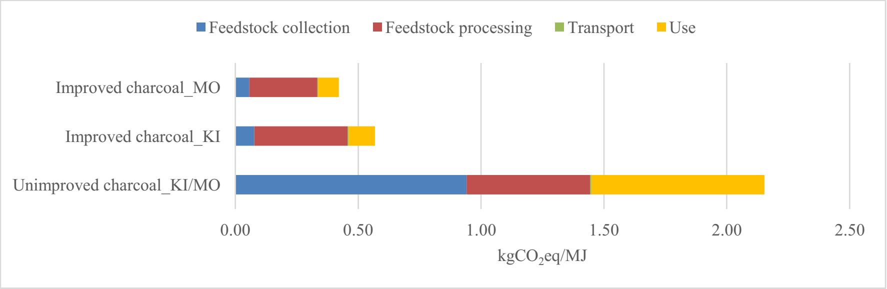

Fig. 4. Carbon footprints (kgCO$_2$eq/MJ) of unimproved and improved charcoal value chains in urban contexts in Kitui (KI) and Moshi (MO).

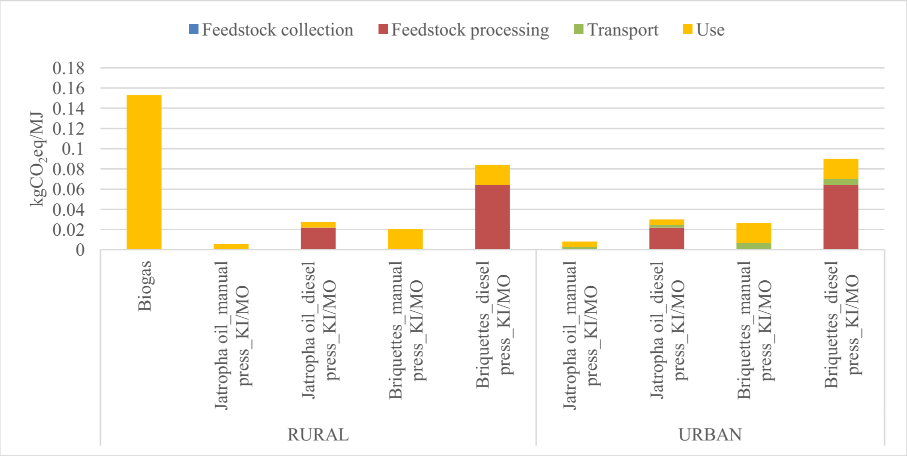

Fig. 5. Comparison of the carbon footprints of alternative biomass energy value chains for rural and urban contexts in Kitui (KI) and Moshi (MO).

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The jatropha oil value chain with the manual oil press has the greatest potential for reducing carbon footprints in both rural and urban contexts in Kitui and Moshi (Fig. 5). However, the environmental benefits derivable from this value chain may be limited due to the small amounts of jatropha seeds that can be obtained from hedges. Since oil production from hedges is the only option that avoids competition with food crops for agricultural land, the question is whether this option can provide sufficient feedstock. It is argued that for jatropha oil to be considered as a substitute for both kerosene and firewood, households would have to increase the length of jatropha hedges on their plots substantially [48]. This might ultimately not be feasible, and the labour input required to harvest seeds from long hedges might be too high for farmers to cope with.

Conclusion and recommendations

Analysis of the carbon footprints of selected biomass energy value chains provides decision-support for the development of policies on biomass energy production and consumption. The results can help decision-makers understand the sources and magnitude of certain impacts of biomass energy value chains, enabling them to focus on those areas most in need of improvement on the path towards socially beneficial development.

Our study indicates that the feedstock collection stage of the firewood and unimproved charcoal value chains significantly contributes to their carbon footprints. Therefore, improving these value chains mainly depends on improving overall forest management such as ensuring reforestation strategy without which wood usage is worse than the other alternatives. Use of *Kenya Ceramic Jiko* and *Sazawa* stoves instead of unimproved charcoal stoves is necessary to realize a significant reduction of the carbon footprint of charcoal combustion in Kitui and Moshi. Moreover, significant research efforts should be directed at improvement of the charcoal production stage of the improved charcoal value chain, where emission reduction so far has remained very small. Finally, our analysis reveals that a switch from firewood to charcoal will lead to further environmental degradation, as its carbon footprint is greater than that of firewood.

The carbon footprint of the biogas value chain is largely influenced by methane leakage during utilization. Improvement of this value chain thus depends on improving biogas burners and gas distribution networks. Overall, the jatropha oil value chain featuring use of a manual oil press appears to have the greatest potential for reducing carbon footprints. However, its potential may be constrained due to the limited amount of jatropha seeds that can be cultivated in hedges on a single farm. Future research should integrate the biophysical, economic, and social dimensions of the jatropha oil value chain, so as to determine its overall sustainability. Prior experience with jatropha in East Africa points to limitations in the economic viability of this form of energy [49].

The jatropha oil and briquette value chains featuring use of a diesel press are in need of improvement. This requires investigating the carbon footprint and feasibility of alternative fuels to power the press, such as jatropha oil that are suitable for both rural and urban contexts in the study sites. Use of a motorized system with sustainable (alternative) fuels would likely increase the production efficiency of briquettes, enabling households to diversify their income sources.

Our research results have the potential to improve development of alternative energy solutions by providing relevant information, raising awareness, and informing stakeholders and decision-makers about possible alternative biomass energy value chains. However, more research is needed. Additional studies of biomass energy value chains and technologies should look at costs related to production as well as factors influencing acceptance and adoption among rural and urban households [50]. This would enable more robust, comprehensive policy recommendations. Household decisions about switching energy sources involve many factors, including technical, economic, and social ones.

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