Bioenergy perspective in Rwanda: The potential of the tree-based system in the agricultural landscape for fuelwood supply

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Abstract

Agriculture is the backbone of the Rwandan economy and employs more than 72.2% of Rwandans. Agricultural land is one of the scarcest resources, and its expansion leads to a decrease in forest areas and other natural resources. Studies on deforestation and forest degradation in Rwanda indicated that the reduction of forest areas has generally been due to the growing population leading to the expansion of agricultural land for food production and a high reliance on biomass as a cooking energy source. This review used different studies and reports to analyze the cause of fuelwood scarcity and the potential of tree-based systems in the agricultural landscape for fuelwood supply. The results indicated that biomass energy would likely remain the primary source of cooking energy, comprising 85% of Rwanda's energy for cooking. Given land scarcity and projected population growth in Rwanda, expanding forests for fuelwood is impossible. Therefore, the study underscores the imperative of integrating trees into the agricultural landscape to address fuelwood demand sustainably. Integrated trees in the agricultural landscape is a fruitful farming system in a land-scarce area to optimize land productivity, reduce pressure on forest areas by supplying fuelwood, and enhance the well-being of rural households by reducing the distance and time spent in fuelwood collection.

Keywords: *Agroforestry, tree-based system, agricultural landscape, fuelwood, bioenergy*

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Introduction

Biomass is the world's most popular energy source, mainly for rural households(Khandelwal et al., 2017). Over 3 billion people worldwide have been estimated to use fuelwood for cooking, water heating, and food roasting (Johnson & Bryden, 2012; Paulsen et al., 2019). Cooking energy remains a significant concern in developing countries, where most of the population primarily uses wood, charcoal, and agricultural residues (Singh et al., 2021). In Sub-Saharan Africa, more than 70% of the population depends on traditional biomass for daily cooking (Ajieh et al., 2023). The cooking energy consumption in East African countries (EAC) is mainly dominated by conventional biomass where the total fuelwoods consumption in Burundi is 96.6% (Sinzinkayo et al., 2015), and in Kenya is 68% for the total energy consumption (Takase et al., 2021). The consumption of biomass as fuelwood in Rwanda is 85% (Hakizimana et al., 2020b), 95% in Uganda, and 90% in Tanzania (Felix & Gheewala, 2011).

The supply or production of biomass in Rwanda consists mainly of firewood and charcoal, primarily used for cooking in rural and urban areas (Hakizimana et al., 2020a). Around 72% of Rwanda's firewood and charcoal come from eucalyptus woodlots planted on the scarce land of smallholder farmers (MINIRENA, 2013). The high dependency causes Rwanda's fuelwood scarcity on wood biomass in different economic sectors where small-scale industries like tea companies and brick production also use firewood (Takase et al., 2021). Since most forests in Rwanda are protected, biomass production relies on privately owned forests, tree-based systems in the agricultural landscape, and small woodlots (Mugunga, 2016; Ndoli et al., 2021). The Rwanda Ministry of Environment (MoE) study in 2018 stated that individual trees in the agricultural landscape generate 10,272,751 m^3 of woody biomass per year. Those biomass are mainly from agroforestry and small woodlots country-wide, representing around 80% of the total volume supplied by forest plantations and seven times higher than the wood biomass provided by shrubs and savanna (MoE, 2016).

Agricultural land is one of the scarcest resources, and its expansion leads to decreased forest areas and other natural resources. Since agriculture is the backbone of the Rwandan economy, more land will have to remain under agricultural use (NISR, 2023) . Biomass energy is also likely to remain the primary source of cooking energy, and Rwanda's population is projected to increase(Banerjee et al., 2020; Hakizimana et al., 2020a). The increasing population with very scarce agricultural land shows the impossibility of expanding the forest areas to meet the fuelwood demand, indicating the contribution of integrating trees in the agricultural landscape for the fuelwood supply in Rwanda(Ndayambaje et al., 2011; Ndoli et al., 2021).

This paper aims to review the potential of tree-based systems (TBS) in the agricultural landscape to supply fuelwood in Rwanda. Adopting fast-growing and coppicing tree species in the agricultural landscape, such as *Eucalyptus spp, Calliandra calothyrsus, and Senna spp,* could generate enough fuelwood in short rotation (Anywar & Labeja, 2022; Marketo, 2022). Integrated trees in the agricultural landscape is a fruitful farming system in a land-scarce area to optimize land productivity, reduce pressure on forest areas by supplying fuelwood, and enhance the well-being of rural households by reducing the distance and time spent in fuelwood collection.

Methodology

A total of 185 studies on bioenergy supply and demand and fuelwood use efficiency have been reviewed, but only 66 have been considered based on the required information. The information mentioned in this review paper comes from some literature, including published articles, reports, a thesis, book chapters, and conference proceedings on fuelwood supply and demands, fuelwood use efficiency, and the potential of tree-based systems in the agricultural landscape for bioenergy supply. The literature was selected based on the title and contents of the abstracts relevant to this review. Online databases, such as Google Scholar, Scopus, web of Sciences, and Science Direct, were used to search the available literature and reports.

Results and Discussion

The gap in the source of bioenergy supply in Rwanda

Traditional biomass, including firewood and charcoal, is the Rwandan population's primary fuel for their energy needs, especially cooking (Hakizimana et al., 2020a). This dependency on biomass for cooking has become the leading cause of the low stock and decline in the productivity of forest plantations due to premature harvesting (Nyirambangutse et al., 2016). A study conducted by RWAFA (2017) on wood supply and demand indicated that the demand-to-supply ratio is 2:1 from forest plantations, and the supply shortage is expected to increase with the growing population if there is non-alternative cooking energy or sustainable planning for fuelwood supply.

The shortage of biomass to meet the demand in Rwanda is estimated to be 4.3 million tonnes, projected to increase to 7.5 million tonnes in 2026 and 10 million by 2050 (REMA, 2021; GoR, 2020; Babu et al., 2022). Almost half of the global forest has to be harvested for cooking energy production to reduce the gaps between the demand and supply of biomass (FAO, 2014).

A study by Rosa et al. (2017) indicated that the fuelwood consumption in Rwanda is 0.3 tonnes per person per year. Considering the total population of 13,773,448 persons in Rwanda (Worldometer, 2023), the estimated fuelwood consumption would be 4,132,034 tonnes per year, significantly more than the estimated supply of 2.3 million tonnes of fuelwood annually in Rwanda by the National Forest Management Plan 2017-2021 (NISR, 2018a).

According to Integrated Household Living Conditions Survey 5 (EICV 5), one household in Rwanda consumes around 1.8 tons of firewood per year for cooking (NISR, 2018a). Still, the demand is high even though other sectors depending on fuelwoods are not considered. The National Forest Management Plan 2017-2021 (NFMP) is anticipated to supply 2.3 million tonnes of fuelwood annually in Rwanda, which is insufficient to meet the demand considering the growing population. To reduce the gaps between supply and demand, there is a need to increase the number of trees in the agricultural landscape, increase wood productivity, and use alternative cooking technologies with high cooking energy use efficiency, such as improved cooking stoves, cooking with pellets and briquettes as an alternative to cooking with firewood in three stones in rural areas and charcoal in urban areas (Ochieng et al., 2013; Scheid et al., 2022; Torres-Rojas et al., 2011).

The potential of TBS in the agricultural landscape for bioenergy supply in Rwanda

The TBS consists of trees planted in the agricultural landscape to generate multipurpose products, including fuelwoods, stakes for climbing beans, wood for construction, animal fodder, fruits, timbers, etc. (Iiyama et al., 2018). Various tree-based systems, including small woodlots, intercropping, live fences, and windbreaks, all allow for planting trees that may be used for fuelwood and timber (Scheid et al., 2022). These approaches provide integrated food-energy systems that maximize the synergies between wood production and crops. TBS in Africa generates 20% of the continent's fuelwood (Sharma et al., 2016). The study on tree cover in Rwanda indicated that 72% of the trees are located in agricultural land and savanna, while 15% are in plantations (Mugabowindekwe et al., 2022). Despite the area occupied by the forest plantation, the productivity rate is still meager, ranging between 2.1–3.5 tones ha-1 year-1, which is insufficient to supply the cooking biomass demand in Rwanda (Ndayambaje, 2013; Ndayambaje et al., 2014; Nyirambangutse et al., 2016).

Compared to supplies from forests and woodlots, producing fuelwood for agroforestry may provide more environmentally friendly options (Ndoli et al., 2021). For instance, picking up branches or gathering deadwood from trees is a common method of harvesting fuel from agroforestry.

When pruned regularly, the TBS produces firewood for cooking and mulch or green manure for soil fertility. Harvesting timber and fuelwood on farms may lessen the burden on surrounding forests and woods and make gathering fuelwood less laborious (Ndayambaje & Mohren, 2011). SSA fuelwood inventory and experiments show large volumes from diverse species under different agroforestry systems (Dlamini, 2020). Depending on agroforestry technique and agro-climatic conditions, fuelwood production from agroforestry may supply up to ten families of 3–7 people with their annual fuelwood needs of 486–500 kg (Dlamini, 2020). Its output is 0.67–0.69 m^3 per capita per year Ndayambaje and Mohren, 2011; Iiyama et al., 2014 and Dlamini, 2020).

A study conducted by Kimaro et al. (2019) in Tanzania showed that, depending on the species and planting spaces, 0.5 to 8 tonnes $ha^{-1}year^{-1}$ of wood biomass could be produced in shelterbelt, farm boundaries, intercropping, and on contour bands in the agricultural landscape. This fuelwood can sustain a five-member family for 4-6 years, cooking the daily household foods when cooking with the traditional three-stone and improved stoves (Kimaro et al., 2019).

Rotational woodlots are the principal fuelwood production technique in semi-arid agroforestry practices for fuelwood production (Kimaro et al., 2007). They enable intercropping with fast-growing nitrogen-fixing plants in the first two years without affecting crop output. After five years, they generate a lot of charcoal and livestock fodder and increase agricultural productivity(Kimaro et al., 2007). Rotational woodlots in Tanzania produced three times more wood than miombo forest vegetation and could provide household fuel for 7–16 years (Kimaro et al. 2007). In Rwanda, western Kenya, and Ethiopia, farmers keep small monospecific woodlots of eucalypts or other fast-growing species for fuelwood, poles, and timber (Ndayambaje and Mohren, 2011; Mekuria et al., 2019;). Rwanda and Kenya have woodlots at homesteads and on hillsides (mostly degraded land). A hectare of 2–3-year-old Sesbania trees in Malawi provided 90% of residential fuelwood (Kamanga et al., 1999). Pigeon pea cultivation and energy-saving stoves have decreased Malawians' need for fuelwood (Orr et al. 2015).

The agricultural land in Rwanda is estimated to be 1.402 million hectares (59.0% of total country land) (NISR, 2022). Considering an average maximum biomass production of 8 tones ha-1 year-1 reported by Kimaro et al. (2019) in Tanzania, in the context of the agricultural landscape of Rwanda, the amount of fuelwood that can be produced would be 11.216 million tonnes year-1, which is bigger than the demand per year. The average landholding per household in Rwanda is estimated to be 0.72 ha (NISR, 2022), with an average of 8 tons ha-1 year-1 reported by Kimaro et al. (2019); this land can produce 5.76 tonnes year-1, which is significantly more than average biomass consumed by one household in Rwanda per year to satisfy their cooking needs. One household in Rwanda consumes around 1.8 tons of firewood per year for cooking (NISR, 2018a); with this scenario, they will need approximately 0.2 ha under 2m width * 2m length Eucalyptus (if production is 7.7 tonnes/ha/year) (Kimaro et al., 2019).

In Rwanda, the most widely used species in small woodlots in the agricultural landscape are *Eucalyptus spp*, followed by *Grevillea robusta* (Mugunga, 2016; Ndayambaje et al., 2014). Shrubs are also found in the agricultural landscape of Rwanda, such as *Senna spectabilis, Calliandra callothyrsus, Gliricidia sepium, Leucaena spp*, etc. (Winowiecki et al., 2021; Kuria et al., 2018). These species are fast growing and indicate a positive impact on fuelwood supply.

Different agroforestry technologies are suitable for Rwanda's agricultural landscape. Intercropping and mixed cropping involve planting trees between the farmers' plots and mixing them with crops for soil conservation, plot delimitation, and erosion control. These practices can generate timber, fuelwood, fodder, and stakes for climbing beans and provide services such as soil conservation and erosion control (Sharma et al., 2012). Live fences mainly comprise indigenous and exotic tree species such as Euphorbia spp and Senna spp (Ndayambaje & Mohren, 2011).

Despite several obstacles, TBS is widely used in Rwanda to help with energy demands. The country's fuelwood energy use has made TBS increasingly important. Though there is little information available on the country's estimated fuelwood production through TBS several bottlenecks prevent Rwandan TBS for fuelwood from progressing. These include insufficient laws, rules, and policies, a lack of planting materialsaccess to markets and value chains, availability of finance, and land tenure.

Policy, agreement, and framework supporting TBS in the agricultural landscape in Rwanda.

The formulated policies and regulations in supporting the TBS in the agricultural landscape are recognized to contribute to (1) sustaining the development of an intensified and productive agriculture through the provision of ecosystem services and the diversification of the production, (2) landscape restoration by increasing the trees cover and (3) promoting the private sector based rural economy through the boosted value chains of TBS in agricultural landscape products (fuelwood, charcoal, fruits, etc.).

TBS in the agricultural landscape is a significant component of the vision of the Green Growth and Climate Resilience National Strategy for Climate Change and Low Carbon Development (REMA, 2011), which aims to reach a developed climate-resilient, low-carbon economy by 2050. Its Program 12 on Sustainable Forestry, agroforestry, and biomass energy' notably proposes a joint strategy for promoting TBS in the agricultural landscape between MINIRENA and MINAGRI. Rwanda's Intended National Determined Contributions (INDC) emphasizes sustainable forestry, TBS in the agricultural landscape, and biomass energy as programs under which specific actions are implemented to achieve direct and indirect mitigation benefits (Orion, 2021). TBS in the agricultural landscape has a high potential to fulfill INDC commitments by reducing emissions from agriculture through carbon sequestration and making it resilient through appropriate investments and innovations. With INDC, Rwanda's target is to reach 100% of the farms implementing agroforestry by 2030 (Hein et al., 2018).

TBS agricultural landscape has gained importance in the new Forest Sector Strategic Plan 2018-2024 (FSSP 2018-2024) (GoR, 2018). This forest sector strategic plan recognizes the issues of managing Rwanda's land scarcity. One solution is increasing tree resources in the agricultural landscape based on the demand for forestry products, including fuelwood, which is higher than the forest product supply (Ndoli et al., 2021). The Forest Investment Plan (FIP) identifies TBS in the agricultural landscape as a critical investment area that will develop TBS in support of sustainable agriculture and environmental protection (RWAFA, 2017). It recognizes that TBS in the agricultural landscape engages local communities, cooperatives, and the private sector. It considerably alleviates poverty through increased crop and livestock (fodder tree) production for smallholder farmers. Hence, TBS is essential for reducing deforestation and forest degradation and enhancing forest carbon stock. Properly implementing all those policies and strategies will be an outstanding contribution for on-farm trees to fuelwoods supply while improving land productivity.

Despite the recognition of TBS, Rwanda still needs robust legislation, policies, and governance structures, enabling institutional capacity, public-private partnerships, transparency and accountability, and institutional financing mechanisms for the sector to boast improved TBS development(GoR, 2018). Agroforestry has been used in Rwanda for some time. With an earlier focus on timber production, agroforestry has been integrated into the forest policy framework developed by the Government of Rwanda (GoR, 2018). Still, more relevant policies and legal frameworks that allow the adoption of agroforestry to boost firewood production in Rwanda are needed.

The rationale for the efficient consumption of biomass for bioenergy in Rwanda

In Rwanda, cooking with firewood is dominant in rural areas, while charcoal is more prevalent in urban areas due to transportation, storage, and other costs (Hakizimana et al., 2020a). In most urban areas, 75% of the households use charcoal as a source of cooking energy, and 95% of the rural population use firewood (NISR, 2018a, 2018b), with 79% of households cooking with inefficient three-stone technologies (Nyaga et al., 2021).

Projected population and urbanization trends suggest that the demand for charcoal continues to increase in Rwanda (Seguin et al., 2019). The average price of charcoal observed on the domestic market is 363 Rwf/kg, while the pellet price was 200 RWF/kg in 2018 (Jagger & Das, 2018a). In Rwanda, the production of charcoal is still done through traditional earth mound kilns, which causes the reduction of the yield of final products (charcoal) and pollutes the environment. A study conducted in Rwanda indicates that the yield of charcoal obtained in a traditional mound kiln based on the weight of wood used was 7.5% (Nahayo et al., 2013). A study conducted in Tanzania indicated that the conventional kiln produces a low quantity of charcoal because of its poor carbonization process, which has an efficiency of 11-25% (Felix & Gheewala, 2011). Further research concluded that charcoal could be replaced by briquettes and pellets for efficiency and effective biomass conversion into high-quality fuelwood (Ibitoye et al., 2021; Lisa et al., 2019; Zanetti et al., 2017).

A study conducted in Kampala indicated that cooking with briquettes in a small household is less expensive than the use of charcoal and has the advantages of reducing waste streams and increasing job creation since most of the feedstuffs used for making briquettes are waste (Ferronato et al., 2018) and unused forest products (Daniel et al., 2022). Briquettes behave and burn very similarly to charcoal, which means the users do not have to change their furnaces or practices. Their primary advantages over charcoal are that they have a longer burning time, do not produce sparks, are slightly less polluting, and offer a consistent fuel quality (Ibitoye et al., 2021). However, the population uses firewood and charcoal due to the unavailability of briquettes in the markets due to the low technologies in manufacturing (Mainimo et al., 2022).

The second technology which can replace charcoal is the use of pellets. Pellets are homogeneous grade fuels that reduce the variability in size, shape, and moisture content associated with most solid fuels (Champion & Grieshop, 2019). Using biomass as pellets is more efficient and cost-effective than charcoal and non-processed biomass for bioenergy production (Picchio et al., 2020). In addition, pellets could be produced from different feedstock, including TBS in the agricultural landscape, crop waste, timber processing waste, unused forest biomass, etc. (Champion & Grieshop, 2019; Lisa et al., 2019; Rahayu et al., 2020).

Using pellet-based stoves is a viable step in households' transition energy. Generally, it reduces the greenhouse gases emitted by traditional cooking stoves and charcoal production (Ibitoye et al., 2021; Jagger & Das, 2018). Combining wood pellets with improved cooking stoves could reduce the amount of fuelwood consumed during cooking, reducing fuelwood's challenges in Rwanda (Jagger & Das, 2018b).

The third method for fuelwood use efficiency is the adoption of improved cooking stoves (ICS). The use of rocket stoves such as kuniokoa stoves reduces fuelwood consumption, according to measurements made in the laboratory (Catalog Clean Kitchen, 2020). It, therefore, offers the potential to significantly reduce indoor emissions (and exposure) compared to traditional cooking stoves and three stones (Champion & Grieshop, 2019). In Rwanda, conventional wood fireplaces can be classified into four types: made of three stones, mainly in rural areas; cylindrical metal stoves, tripod metal, and clay stoves, mainly used in urban areas burning by using charcoal (Hakizimana et al., 2020a).

A study on ICS in Malawi by Wathore et al. (2017) found that well-dried biomass and cooking using ICS were critical in reducing household fuelwood consumption compared to the traditional three stones. The study conducted in Rwanda indicated that cooking with pellet and ICS may be able to offer customers health and climate advantages over other cooking fuels and also reduce the socio-economic constraints that most households face in accessing clean cooking fuels (Champion & Grieshop, 2019; Rahayu et al., 2020).

A gender perspective on bioenergy supply and demand in Rwanda

The shortage of fuelwood affects more women and children as they are known to be the primary fuelwood collectors for home cooking and sale at local markets (Njenga et al., 2017; RWAFA, 2017). Women sometimes travel long distances in the field and carry heavy loads of firewood (Ondiba & Matsui, 2021). A study in Ghana indicated that women and children, especially girls, walked a distance of 5.2 km and spent more than 4.5 hours per week on fuelwood collection (Alirigia, 2019). Babalola's (2018) finding in Nigeria indicated that women and girls are the only ones responsible for firewood collection, and they used to walk more than 2 km twice a week to carry firewood. This has a negative impact on their economic activities, and children may not attend school due to the collection of firewood (Njenga et al., 2017).

The Sustainable Development Goal (SDG) 7 aims to ensure affordable, reliable, modern, and sustainable energy for all (Bank, 2010; Ahmad et al., 2020). The assessment of the progress of this goal is based on the household's access to cooking energy and other daily activities (UN-Environment, 2019). Considering the purposes of SGD (goal 7), improving access and fuelwood use efficiency in urban and rural households in Africa will positively impact the lives of low-income families, especially women and children (Mudaheranwa et al., 2019).

Regarding the harm caused by cooking using inefficient stoves and poor-quality fuelwood, the consumption patterns and the quality of fuelwood will positively affect the achievement of SDG goal 3 (health and well-being) (Hakizimana et al., 2020b; Tamire et al., 2018). Using inefficient cooking stoves is a source of air pollution and causes the premature death of around 600,000 people yearly in Africa (Babalola, 2018). Babalola's (2018) finding in Nigeria indicated that most households use three stones for cooking, but women prefer to use the improved stoves due to the unavailability of firewood. The lack of access to clean energy and efficient cooking stoves exposes women to health hazards by exposing them to smoke (Gitau et al., 2019). A study conducted in Ethiopia indicated that women and children stay more in the kitchen and have health risks due to exposure to smoke (Tamire et al., 2018). Research conducted in rural villages in western Kenya indicates that 92% of women and 95.4% of children have been affected by cooking smoke, where the use of fuelwood is discovered to be associated with the increase in coughing, phlegm, wheezing, headaches, and eye problems (Dida et al., 2022).

Given that women are much affected when there is a shortage of fuelwood, the fuelwood use efficiency has a positive impact on Goal 5 (gender equality) and improves the energy supply and consumption, which is less than the demand related to Goal 7 (energy), while reducing the pressure on forest plantation will lessen the negative impact of climate change (Goal 13) (Torres-Rojas et al., 2011; Ochieng et al., 2013; Njenga et al., 2017; Hammar et al., 2019).

The adoption of TBS in the agricultural landscape for increasing the supply of fuelwoods while protecting the environment will directly impact the achievement of Goal 15 (cover, restore, and sustainably use natural resources) (World Bank, 2010; U.N., 2018; MININFRA, 2019).

Conclusion

The use of biomass-derived from trees as a source of energy is still prevalent today and looks to be growing in importance, given the limited availability of fossil fuels, together with the expansion of population and industry. Given the small size and low productivity of forest plantations, which is impossible to expand due to land scarcity with Rwanda's increasing population, the primary fuelwood source is tree-based in the agricultural landscape. The trees-based systems in the farming landscape have a high potential to provide fuelwood sustainably in Rwanda due to their fast growth and quick coppicing ability. Integrating fast-growing and multipurpose tree species in the agricultural landscape is crucial for promoting the increased production of on-farm tree biomass.

Incorporating trees in the agricultural landscape will support the maximization of land profitability by improving cooking energy access, reducing the pressure on forest plantations, and increasing rural smallholder farmers' income. The fuelwood access and use efficiency will directly impact the well-being of women and children who are known to be in charge of collecting the fuelwood and sometimes have to travel long distances to collect heavy loads of firewood.

Declaration of Competing Interest

This research has no conflict of interest.

Acknowledgment

The authors acknowledge the funding provided by Sida under grant number 13394 to the Regional Research School in Forest Sciences (REFOREST), College of Forestry, Wildlife, and Tourism, Sokoine University of Agriculture, P.O. Box 3009 Chuo Kikuu, Morogoro, Tanzania.

Conflict of interest

This manuscript has no conflict of interest and has not been published anywhere by the authors.

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