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LETTER

Sustainable woodfuel systems: a theory of change for sub-Saharan Africa

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Abstract

Charcoal and firewood, together comprising woodfuel, are key in the cooking energy mix in sub-Saharan Africa (SSA). Charcoal is made by burning wood under controlled oxygen to arrive at a product high in carbon. Firewood is wood burned directly to provide energy. Wood energy, which is gaining in popularity as a sustainable fuel in developed countries, is characterized as a driver of land degradation on the African continent. Instead of wishing for the demise of woodfuel due to its associated negative health and environmental impacts, a systems thinking approach argues that improving technologies and efficiency in wood production, charcoal and firewood processing, transport and trade, and utilization in a circular bioenergy economy meets a range of needs while conserving the environment. This article outlines a sustainable woodfuel theory of change (ToC) that describes how woodfuel can be made sustainable rather than being dismissed as a transitional fuel on its way out. The ToC is based on the knowledge that no energy system is without flaws and that technologies exist for real quantifiable improvements in woodfuel systems while filling the energy-poverty gap. A bold rational decision must be made in rethinking woodfuel in SSA, as failure to advance woodfuel technologies undermines global efforts directed towards land restoration and climate change mitigation. We recommend that an improved and sustainable woodfuel system should be considered as an acceptable modern energy source under SDG 7.

1. Introduction

Globally, over half the wood harvested from forests is used for traditional woodfuel (charcoal and firewood) mainly for cooking and heating (FAO 2013). About one-third of the world and 90% of Sub-Saharan Africa's (SSA) population relies on solid biomass using traditional cooking appliances (IEA 2017). Bioenergy contributes more than 60% of energy mix in SSA. Africa produce 32.4 tonnes of charcoal which is 62% of the global production most of it being produced in Eastern (42%), Western (32%) and Central (12.25) Africa (FAO 2017). Woodfuel is preferred for its affordability, accessibility, and compatibility with cooking culture, including availability in the form and amounts required. Inefficient production and use results in diverse negative environmental and health impacts, including degradation of woodlands and severe and chronic respiratory problems (Li *et al* 2021). These negative impacts have resulted in efforts to shift from woodfuel to other forms of cooking energy with a noble aim of addressing the adverse implications associated with its use. Rather than adopting the new technologies and energies wholesale, however, households tend to supplement wood use with the new cooking technologies and energy sources, a practice called 'stacking' (ESMAP World Bank 2021). This phenomenon leaves policy makers frustrated, although it is typical in kitchens around the world where new cooking devices (e.g., Instant Pot) do not replace existing technologies (e.g. wood baking ovens). Instead of presenting wishful thinking about the demise of woodfuel use in SSA, this article advocates for a culturally realistic rethinking of woodfuel as an important and integral part of the cooking energy mix.

When considering the threat of climate change and the well-being of individuals and communities in SSA, the question of household energy use for cooking and heating provides a useful lens for analysis. There is no question that economic development is inextricably linked to energy for both industry and household use (Liu and Hao 2018, Li *et al* 2021). Improving the affordability and efficiency of cooking and heating plays a central role in improving living standards for many on the continent Ezzati *et al* (2017). The designation of some household fuels as 'modern' or 'clean' is both misleading and reeks of colonialist assumptions about the relative status of Africans versus inhabitants of wealthier countries. This discourse is particularly inappropriate in regard to the use of biomass for energy, which has enjoyed a resurgence in North America and the EU countries over the past decade, and which is appreciated as a renewable resource in the US (Buoncore *et al* 2021; US energy admin.).

1.1. Sustainable woodfuel theory

The ***sustainable woodfuel theory* of change (SWToC) *states that woodfuel can be made truly sustainable in the long run.***Sustainable woodfuel implies addressing the negative impacts at every stage of its production, processing, transportation, and use while optimizing socio-economic and cultural benefits and transforming the environmental co-benefits. This includes the health, production and climate change implications of biomass use for fuel. Trees are a renewable resource that tap solar energy, and as long as harvesting does not exceed replenishment, their use can be sustained indefinitely. To address the negative impacts associated with traditional woodfuel use, governments in SSA are developing strategies to increase tree cover and cleaner cooking technologies and practices to meet their Nationally Determined Contributions (NDCs) to mitigate against climate change, and sustainable woodfuel is a critical component in meeting these goals (MoE Republic of Kenya 2020).

Let us not take for granted access to affordable cooking and heating fuel for the poor, both in urban and remote rural locations. In this regard key components of affordable cooking and heating fuel are social, economic as well as technical. In low- and middle-income countries the energy needs of the poor must be included. This is difficult given that the poorest Africans are not an attractive market for for-profit businesses. Currently the firewood and wood used for charcoal is nearly free, and a more sustainable replacement system must address the needs of that segment of the population if it is to succeed. One of the biggest challenges currently is that public-private partnerships struggle in environments where the profit margins, even under optimal design conditions, are essentially zero.

The SWToC connects the four main components of the woodfuel life cycle, including sourcing wood, processing wood into firewood or charcoal, transport and trading, and utilization (figure 1). The SWToC is based on the knowledge that unsustainability and inefficiencies exist in each component, and it offers evidence-based solutions for transformation to sustainable and efficient at each stage. Improving efficiency in one component of the system has implications on another (figure 1). For example, the degree of efficiency in regard to consumption impacts consequent demand by affecting amount of wood required for processing and transportation. Likewise, the degree of efficiency in processing impacts the amount of wood required and area required to grow it. Further, the degree of efficiency in transportation, marketing, and trade affects access to affordable energy, need for processing, and amount of wood required.

Along the same lines are other concepts such as greening the charcoal value chain to mitigate climate change, and improving local livelihoods through agroforestry combined with improved kilns and stoves to reduce the land area for woodfuel production (Iiyama *et al* 2014, FAO 2017). This SWToC is in line with the urgent actions recommended in the desk study by UNEP and African Union towards making woodfuel sustainable in Africa (UNEP 2019).

The sustainable woodfuel ToC integrates circular bioenergy economies where by-products at one stage are used as inputs for energy or other processes, closing the resource flow loops while reducing waste and pollution. This way, the woodfuel system positively impacts other biological and social systems.

1.2. Why sustainable woodfuel theory of change?

Woodfuel use in less developed regions of the world is relevant to just about all the Sustainable Development Goals (SDG), and especially to SDG 5 on Gender Equality, SDG7 on Affordable and Clean Energy, SDG13 on Climate Action, and SDG15 on Life on Land. In fact, some of these SDGs call for a reduction or end to the use of woodfuel. Solutions offered under each goal focus on improved technologies and alternative fuels, but we argue that solutions should be rooted in social patterns of use. Household choice is a key factor to understanding why people use certain cooking fuels and cooking appliances (Hollada *et al* 2017, Gitau *et al* 2019a), and without an awareness and value assigned to this factor, any solution is likely to fail. Rather than ignoring, or worse,

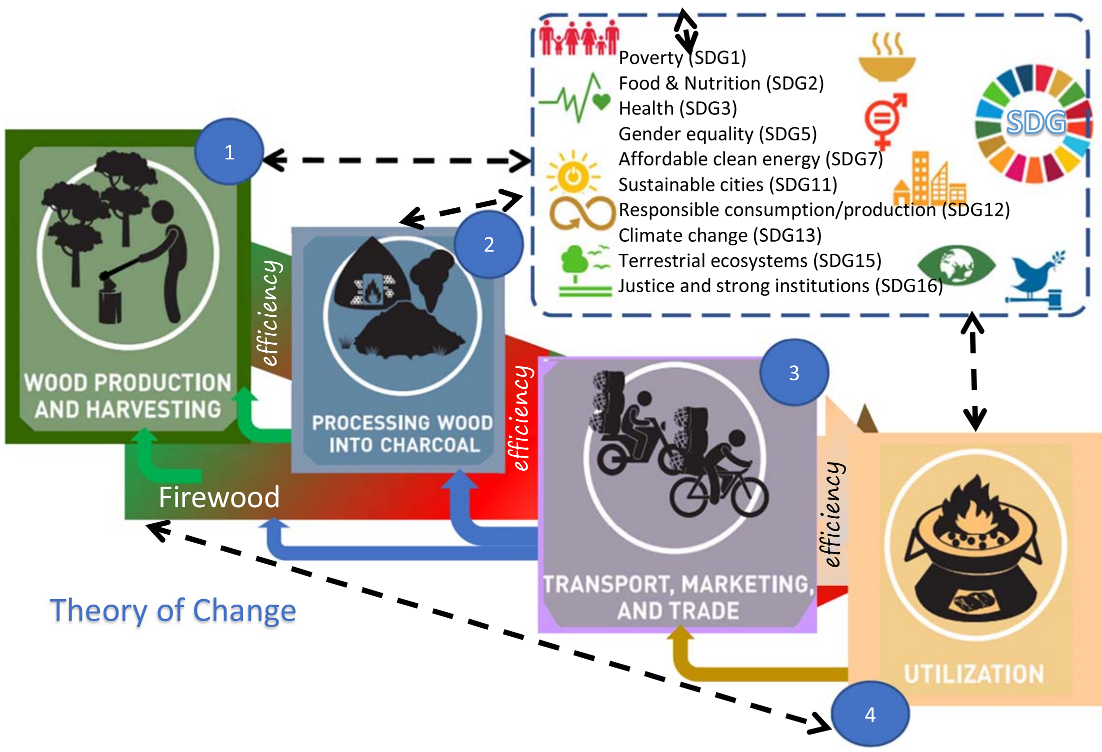

Figure 1. Components of the woodfuel system, interactions among them and socio-ecological impacts: (1) production, (2) processing, (3) transport, marketing and trade, and (4) utilization.

disparaging, woodfuel, people's needs and preferences should be integrated into global research and development, as described by Mendum and Njenga (2018).

At the same time, we highlight a double standard. While woodfuel use by the poor strata of societies is discouraged in SSA, wood is promoted as a modern fuel and a national strategy to reduce greenhouse gases in other continents, especially in the EU. For example, the United Kingdom's Renewable Heat Incentive, introduced in 2014, explicitly includes payment to households using biomass boilers as part of the strategy to reduce the country's greenhouse gas emissions by 80% from 1990 levels by 2050 (OFGEM 2018). A proportion of the charcoal used for barbeque in the global north is sourced from the global South where, for instance, EU in 2019 imported 0.75 million tonnes from the tropics and sub-tropics (Haag *et al* 2020). This points to the need to rethink woodfuel around the world; the unanswered question is why the double standard.

2. Transforming the woodfuel system

Opportunities exist to transform wood production, charcoal and firewood processing, transportation and trade, and woodfuel utilization. Improving the woodfuel system will then enhance sustainability, equity and efficiency while integrating a circular bioeconomy.

2.1. Sustainable wood production

Unsustainable harvesting of wood for firewood and charcoal contributes to land degradation, deforestation and climate change. With respect to land degradation and deforestation, charcoal is of greater concern than firewood as more biomass is required for conversion to charcoal (Drigo *et al* 2015, Njenga *et al* 2017). Further, firewood is mainly gathered from forest residues such as dead wood in natural forests, twigs and branches after timber harvest and poles from plantation forests and trees on-farm (Githiomi *et al* 2012, Mendum and Njenga 2018, Gitau *et al* 2019a). It is the case that as the population of SSA increases, forest residues become more scarce and the distance people must walk to gather wood increases. It is thus important to supplement and expand the forest cover in areas where residue collection occurs. In the case of charcoal, producers either clearcut entire stands or selectively harvest preferred species or use tree residues after clearing for agriculture or invasive tree species control (Iiyama *et al* 2017, Mbaabu *et al* 2019). Harvesting trees for charcoal is prohibited in protected forests in most if not all countries. If governments would enforce existing regulations, much of the blame for deforestation by woodfuel harvesters would be eliminated.

Technologies exist for scaling sustainable wood production for energy, especially on farms and in landscape restoration (table 1). Growing and managing trees for bioenergy present benefits in multiple ways while integrating a circular bioenergy economy. The trees provide additional ecosystem services, such as provision of shade, fruit and fibre, carbon capture (even if temporary), and soil stabilization (de Leeuw *et al* 2014). Additional benefits are provided when trees are produced in agroforestry systems where over 20 times more above-and below-ground carbon is found to accumulate than in conventional farming, especially for systems incorporating fertilizer trees (Kaonga and Bayliss-Smith 2009). For optimal benefits in carbon capture, tree replacement and management should ensure a continuous standing biomass.

2.2. Enhancing technologies for processing

Traditional producers can transition to more efficient, context-specific technologies for wood processing with concerted efforts in capacity development, integration of local practices and gender considerations, affordable credit facilities, and enabling policy with incentives for compliance.

Traditional earth mound kilns for converting wood to charcoal have low recovery rates, leading to wood wastage and air pollution (FAO 2017). Despite their known negative effects, their use prevails given that they are simple to construct, flexible in size and shape, and mobile. Traditional kiln technology is also low cost and requires only informal labour. Improvements in combustion efficiency during charcoal production reduces both wood input volume and GHG emissions, ultimately contributing to a circular bioenergy economy (table 2, figure 2). For example, improving traditional, inefficient kilns can reduce GHG by 80% for a 100-year Global Warming Potential and reduce the amount of wood required and the area needed to grow it (FAO 2017).

The introduction and adoption of improved kilns has faced challenges since they require advanced knowledge and higher capital investment. Some of them are stationery, requiring charcoal producers to spend additional resources to move wood (Iiyama *et al* 2014).

Integral to technology development is the enhancement of producer knowledge. For example, training on wood drying prior to charcoal production, stacking wood in the kiln, kiln ventilation, and generally monitoring the process significantly improved kiln wood to charcoal conversion efficiency from 7% to 22% in the Democratic Republic of Congo (DRC) and 15% to 22% in Kenya (Schure *et al* 2019, 2021).

To contribute to circularity, the emissions and waste pieces of the carbonization processes can be recovered and converted to other uses. For example, in Brazil, the metallic Rima Container Kiln (RCK) converts 35% of the initial wood to charcoal while producing thermal power (Vilela *et al* 2014). Work by Bailis *et al* (2013) in Brazil showed that shift from a hot-tail kiln to metal 'container kilns', which were being tested as a more efficient alternative, reduce greenhouse gas emissions and allow easy capture of pyrolysis gases for production of heat and power. Smoke from traditional kilns can be converted to wood vinegar by condensing captured smoke into liquid. Wood vinegar is used in organic farming to control disease, pests and weeds; for enhancing growth and fruit quality; and for wood preservation and flavouring food (Theapparat *et al* 2018). Pieces of charcoal too small to burn, called biochar, can serve as a soil amendment (Jeffery *et al* 2013, Sundberg *et al* 2020) or are recovered and mixed with a binding agent such as molasses a waste product from sugar factories or soil and compacted into solid units to produce charcoal briquettes (Njenga *et al* 2014).

Transporting woodfuel is a source of GHG in commercial scale, and the resources saved by using waste materials to make briquettes can be undermined if the end product has to be trucked for long distances. A Life Cycle Assessment (LCA) of briquettes produced using sugarcane waste in Western Kenya showed that the transportation of the briquettes accounted for over 60% of the GHG of the system (Laula *et al* 2019) because the end users were tea factories located in Central Kenya. As a solution to the high GHG emissions cost of transport in the woodfuel sector, it is recommended to produce wood and other types of biomass for energy near sites of consumption. Coordinating transportation for the charcoal value chain from rural to urban centers should aim at bulking and carrying large quantities to cities while having the vehicles transport another product back to the rural area to minimise the emissions associated with carrying the fuel.

2.3. Sustainable utilization in cooking systems

There is a clear need to improve woodfuel cooking systems for human health. In SSA, each year over half a million premature deaths are linked to indoor air pollution caused by cooking with fossil fuels and woodfuel (IEA 2017). Other deaths, though not officially accounted for, may be attributed to under-nutrition resulting from women and children walking long distances to collect firewood (Li *et al* 2021).

Fine particulate matter ($PM_{2.5}$) is a common indicator of the health risk associated with exposure to air pollutants from diverse sources (Lim and Vos 2012). Firewood combustion in the kitchen causes over 100 times higher concentrations of $PM_{2.5}$ compared to charcoal (Njenga *et al* 2017).

More efficient woodfuel stoves can help to lower demand for wood and reduce household air pollution (table 3). Switching to cleaner biomass cook stoves in Asia and Latin America improved health outcomes

Table 1. Tree production systems and wood yield in sub-Saharan Africa.

Production system	Tree species	Years to maturity	Yield t/ha	Comment	Source
Woodlots	*Greville robusta*	3–5	2.6		Kimaro *et al* 2019
	Acacia auriculiformis	10	145		Proces *et al* 2017
Boundary planting	*Acacia polyacantha*	3–5	4.4		Kimaro *et al* 2019
	Eucalyptus camaldulensis	3–5	7.7		Kimaro *et al* 2019
Intercropping	*Gliricidia sepium*	2	1.3	Nitrogen fixing	Kimaro *et al* 2019
Natural regeneration of native species	*Acacia drepanolobium*	24	18	Rotational cycle can be reduced with improved management	Okello *et al* 2001
Conservation in a Acacia-Commiphora dryland forest		on-going		The Kasigau Corridor REDD Project, Kenya. Pruning of 20%–50% of stems >5 cm in diameter used for charcoal, residues used for briquette production	Wildlife works https://wildlifeworks.com/
Management and utilization of invasive tree species	*Prosopis juliflora*	3	52	Invading at a rate of 640 ha per annum, nitrogen fixing tree	Mbaabu *et al* 2019

Figure 2. Traditional earth mould kiln in Tanzania (left) and Silos kiln from which gaseous energy is used for district heating at Umeå, Sweden (right). Photos: Mary Njenga/ICRAF (left) and Hakan Örberg (right).

Table 2. Charcoal yield efficiency from various kilns in SSA and Europe.

Kiln technology	% Efficiency	Source
Traditional early mould kiln in Kenya	7, 14	Okello *et al* 2001, Schure *et al* 2019
Improved early mould kiln in Democratic Republic of Congo (DRC) and Kenya	21–27	Oduor *et al* 2006, Schure *et al* 2019, Schure *et al* 2021
Drum kiln in Kenya	28–30	Oduor *et al* 2006
Half orange kiln in Kakuzi Ltd, Kenya	33	Njenga *et al* 2014
Silos in Sweden	44	Njenga 2012

Table 3. Reduction in wood and charcoal fuel use and concentrations of $PM_{2.5}$ by improved stoves compared to traditional cooking appliances in SSA.

Place	Stove/fuel	% fuel saving	% reduction of $PM_{2.5}$	Source
Firewood				
Kwale, Kenya	Gasifier (Gastov)	32	79	Gitau *et al* 2019b
Embu, Kenya	Gasifier (Galvanized)	40	89	Njenga *et al* 2016
Rural, Kenya	Rocket mud	34		Ochieng' *et al* 2013
Western, Kenya	Gasifier	27		Torres-Rojas *et al* 2014
Ethiopia	Improved cook stove	20–56		Duguma *et al* 2014
Charcoal fuel				
Kenya	JikoKoa	26	77	Kirimi *et al* forthcoming
Kenya	Briquette		88	Njenga *et al* 2014

(Alam *et al* 2006, Clark *et al* 2013). Research in the US showed that improving ventilation can also reduce indoor air pollution caused by cooking (Ampollini *et al* 2019, Farmer *et al* 2019). International standards for testing fuel use efficiency, total emissions, indoor emissions, and safety of biomass cook stoves are certified by the International Organization for Standardization (ISO) (https://iso.org/standard/66519.html).

Use of firewood is compared to open fire, industrial Jikokoa is compared to Kenya Ceramic Jiko and briquettes (charcoal dust 80% and 20% soil) are compared to charcoal in KCJ

Improving woodfuel cooking systems also contributes to planetary health by reducing both harmful black carbon and GHG emissions. Combustion of woodfuels globally constitutes 25% of atmospheric black carbon, which is a major component of particulate matter and one of the largest contributors to climate change (WHO and Climate and Clean air Coalition 2016). Emissions from woodfuel are 1.0–1.2 Gt CO_2e yr^{-1} representing 1.9%–2.3% of global emissions (Bailis *et al* 2015). Successful deployment and utilization of 100 million improved stoves could reduce this by 11% to 17% (Bailis *et al* 2015). If black carbon was included in carbon markets, at US$11 per tCO2e of avoided emissions, these reductions would be worth over US$1 billion yr^{-1} (Bailis *et al* 2015). Further, a shift from traditional stoves to improved stoves could result into a 63% reduction in GHG emissions from charcoal in a 100-year Global Warming Potential (FAO 2017).

Applying a circular bioeconomy perspective in woodfuel cleaner cooking has been demonstrated where, for example, a pyrolytic gasifier cook stove burns dry biomass under controlled oxygen, and the gaseous energy is used for cooking and/or heating while char is produced as a by-product. The harvested char is used as fuel or as biochar for soil improvement with additional benefits of mitigating climate change (Njenga *et al* 2021a).

Enablers and barriers for adoption of improved biomass stoves have been studied widely, and this new knowledge needs to inform development towards cleaner cooking (Goodwin *et al* 2015, Brooks *et al* 2016, Kumar *et al* 2016, Puzzolo *et al* 2016, Yip *et al* 2017). Factors such as convenience of use, heating space, reduced fuel consumption and associated time and cash expenditure, and reduced household air pollution are some of the documented enablers for adoption of improved cook stoves (Agbokey *et al* 2019, Gitau *et al* 2019a). Functional characteristics such as need to cut firewood into small pieces, continued management of fuel, need to refill fuel canister and relight the stove in the middle of cooking, size of stove, household size, type of food and cost of stove and repairs are some of the key identified barriers inhibiting adoption of improved stoves (Hollada *et al* 2017, Agbokey *et al* 2019, Gitau *et al* 2019a). Compatibility with local cooking culture summarises most of these barriers, though the knowledge possessed by women as main cooks often has been overlooked.

2.4. Equity and efficiency in woodfuel system

Gender disparities characterise both household and commercial sectors of the woodfuel economy in sub-Saharan Africa. With few exceptions, the labour burden for household firewood collection falls entirely on women, who generally collect and transport bundles of wood on foot. Unfortunately, the literature on biomass energy, renewable energy use and technology does not include a comprehensive analysis of important issues such as the economic value of time spent currently on inefficient woodfuel activities or the gendered distribution of household woodfuel use versus even the most low-levels of commercial activities. A comprehensive survey of the most recent literature on renewable energy in Africa, for example, shows a focus on technology and non-wood biomass options (Afrane *et al* 2022). Even studies of energy use among the poor in Africa focuses on charcoal and biogas without considering the entire woodfuel system (Karakezi 2002).

At the household level, the barriers to studying the portion of the woodfuel system used by rural and urban populations, including refugees, include lack of funding for study of the social—as opposed to the technical—factors that influence the use and innovation around woodfuel use. Until very recently, donor organizations and governments have focused on transitioning to 'modern' energy sources, including fossil fuels like LPG, or renewables like solar energy for electricity generation. Neither of these options addresses the majority of household users in Africa, namely poor and middle-income women. There exists a rich literature on informal work on the continent, again, not specific to woodfuel use but which would provide a useful structure for a detailed study of this kind (Khavul *et al* 2009, Lindell 2010, Jackson 2012, Grant 2013).

One additional issue that is important to understanding woodfuel use is the legal situation regarding refugees who use woodfuels harvested from local resources, often in arid areas. The wars and political instability in South Sudan, the Democratic Republic of the Congo and Somalia have resulted in substantial refugee populations in East Africa, for example. The civil war and continuing conflict in Ethiopia has exacerbated the large numbers of individuals on the move. With the exception of Uganda, which has a unique and inclusive approach to refugee integration, refugees are not allowed to work or travel freely outside of UNHCR camps set up for their accommodation. This means that the economic potential of refugees is difficult to measure empirically and the environmental and human damage done by mismanaged or unmanaged woodfuel collection and use systems has a substantial unmeasured impact on people, animals, and the larger environment. The same situation in also true in other parts of the continent with similar results.

In the commercial sector, women tend to be involved in the low-income segments of the woodfuel market such as in production and retailing of charcoal. Their male counterparts dominate segments further down the supply chain, such as transportation and wholesale trade, where profit margins are higher (Ihalainen *et al* 2020). This gender disparity is associated with access and control over productive resources and income, social and political capital, and gender roles and responsibilities (Ihalainen *et al* 2020).

There is need for gender equality enhancement in benefit sharing, which could be achieved through gender analysis and gender integration along the value chains for enhanced socio-economic sustainability. Wood production and processing technologies are often tied to the availability of transport, which is governed by who controls the modes of transport. Transport, marketing, and trade are highly gendered.

3. How to make transformational change in woodfuel sector

A systems approach to a transformative shift to sustainable woodfuel requires processes that link complex social conditions, cultural preferences, biological systems, and technologies. An inclusive approach requires blending distinct knowledge systems, including local, traditional and scientific, and appreciating user preferences and capacities. Involving multiple stakeholders in these processes allows for the co-design of technologies, co-production of knowledge and co-implementation of actions, as well as the conduct of reflective monitoring of impact in a co-learning atmosphere. An array of innovative methodologies and tools are available to drive transformative change in the woodfuel sector.

The first is to use participatory transdisciplinary (TD) techniques (Lang *et al* 2012). TD teams from diverse disciplines form a research-in-development community that can transcended the boundaries between science and policy, social development and technological change, and research and implementation. The community effectively engages diverse actors with a stake in woodfuel, including individuals, community-based organizations and opinion leaders, non-governmental organizations, and policy makers.

Second, a co-research model with elements of citizen science fosters diverse stakeholder engagement and communication techniques that enhance active participation of the public in scientific research. This approach enables the integration of end users' needs, preferences, potentials, limitations, and local knowledge in both research design and technology development. For example, in the living laboratory approach, women cooks were part of the research and innovation team as opposed to being study subjects (Njenga *et al* 2016, Gitau *et al* 2019a, Njenga *et al* 2021).

A third tool, especially effective for context analysis, visioning and stakeholder engagement, is the Stakeholder Approach to Risk-informed and Evidence-based Decision-making (SHARED), developed by World Agroforestry (ICRAF) specifically for sustainable woodfuel systems (Chesterman *et al* 2018). Associated activities include stakeholders carrying out problem analysis and prioritization of interventions.

Tools to measure change are essential to monitoring, reporting and verification of impacts. The Land Degradation Surveillance Framework (LDSF) is applied to measure changes in land use, land cover, landform habitat, soils, and land degradation that helps show effects of unsustainable wood sourcing for woodfuel (Vågen *et al* 2018). A life cycle assessment (LCA) and Global Bioenergy Partnerships (GBEP) Indicators (Laula *et al* 2019) are also effective for measuring impacts of woodfuel system components on livelihoods and the environment, including climate change. These tools and methods help to identify geographic hotspots and nodes in woodfuel system that have positive and/or adverse social, ecological or environmental impacts, including on specific actors.

The issues and challenges associated with each component of the woodfuel system differentially affect demographic groups, such as women, youth and children. Consequently, sustained transition to sustainable woodfuel systems requires an understanding of how overarching challenges and existing opportunities are experienced differently by members of each group, as well as those that are unique to each. Thus, a transformation towards sustainable woodfuel systems especially requires effective gender integration using tested guidelines and methodologies that can be adapted to local context (UNIDO 2014).

4. Development outcomes of sustainable woodfuel systems and further research and development work

Prohibiting the use of woodfuel by low-income families and requiring instead a shift to other forms of energy is not only impractical but also serves to further alienate and impoverish the rural poor. The sustainable woodfuel theory of change posits that shifting current practices in wood production and harvest and improving processing and use toward sustainability, rather than eliminating the sector altogether, can contribute to the achievement of many of the SDG targets. These include especially SDG 5 on Gender Equality, SDG7 on Affordable and Clean Energy, SDG13 on Climate Action, and SDG15 on Life on Land.

The optimization of resource recovery and reuse (RRR) in all components of the sustainable woodfuel system contributes to the circular bioenergy economy while minimizing waste and pollution. This is achieved through the collection and use of even the smallest twigs from the raw wood material to make charcoal or fuel briquettes; the capture and transformation of wood smoke, steam and other emissions for biomaterial or bioenergy; and the repurposing of small, discarded bits of charcoal as a soil amendment material or aggregation into fuel briquettes.

The sustainable woodfuel system also helps to increase income for multiple actors along woodfuel-based value chains and improve food and nutrition security. Poor access to affordable and reliable cooking and heating fuel denies families the opportunity to cook food properly, forces them to skip meals and change diets, and results in inordinate spending of the household income on fuel. All of these factors result in household insecurity around income, food, and nutrition (Sola *et al* 2016). For charcoal producers, improving efficiency in the transformation of wood to charcoal increases yields, income and employment, contributing to household and community poverty alleviation and to the national economy while reducing wood demand (FAO 2017). The repurposing of small fragments of charcoal, otherwise wasted, as biochar sequesters carbon and improves soil conditions, consequently increasing crop yields with both financial and food and nutrition benefits and is a good climate smart agriculture innovation for drylands (Sundberg *et al* 2020, Njenga *et al* 2021b). Access to affordable and convenient energy allows families to boil water, reducing waterborne diseases and cook food properly, allowing for complete nutritional gains.

Critically, supporting a sustainable woodfuel system can boost gender equality and spur inclusive innovations, such as improving the production of woody biomass on farms. Accessing firewood from trees on farms increases supply of firewood and brings this resource closer home, while surplus is sold for income generation (Kimaro *et al* 2019, Njenga *et al* 2021b). It also reduces the energy burden on women and children and the associated risks inherent in the unpaid labour of gathering and hauling wood from forests and woodlands (Mendum and Njenga 2018, Njenga *et al* 2021). Improved cooking appliances also reduce time spent by women on cleaning soot from cooking pots (Gitau *et al* 2019a). The time saved can be used for other productive purposes or leisure. Recently, schemes have been developed to sell 'time saved' as units to donors and funds invested in women empowerment, as demonstrated by WOCAN's W+ standards (http://wocan.org/what-we-do/wstandard).

Further research, development and policy work is needed to support the shift towards sustainable woodfuel systems in SSA. For instance, there is need for studies on production and use of wood for meeting energy needs across the countries to inform national and regional policy development. At its core, a transformation requires the implementation of evidence-based technological innovations aimed at solving societal challenges and driven by curiosity about modernizing woodfuel from a system perspective. The technologies should take into consideration economic benefits, socio-cultural values and prestige, ease in monitoring outcomes, compatibility, environmental impacts, and system circularity to reduce waste and pollution. Research into local resistance to new technologies should emphasize compatibility with end user needs, and results can inform effective communication to a diverse range of stakeholders for enhanced demand and support for technological advancement for sustainable woodfuel systems.

Policies and investments should allow for the common practice of energy mixing, especially at the household and community levels, rather than funding the expansion of centralized energy systems by granting exclusive licences to providers tied to any one fuel type. Long-term energy independence should be a policy goal rather than profit margins for current businesses. Research can support innovative energy policies, strategies and programs at local, national and regional levels to integrate sustainable woodfuel systems into energy policy, with co-benefits in other development goals.

5. Conclusions and recommendations

The sustainable woodfuel theory of change is based on the viability of solutions for eliminating the quantifiable negative health and environmental impacts of woodfuel harvest, processing, transport and trade, and use. The new proposition is a paradigm shift to considering woodfuel as a source of energy for the future as opposed to a transitional fuel on its way out. It counters the prevailing notion and emerging policies that propose to eliminate woodfuel use by the poor, replacing it with petroleum-based fuels, while at the same time encouraging it in wealthy nations (e.g., wood pellets, wood chips).

The first critical consideration made in this proposition is the recognition that improvements must adopt a systems approach by addressing all the four components of the woodfuel system—wood production, processing, trade and transport, and consumption—and understanding the interactions among them. The systems approach is further integrated through a circular bioeconomy based in the recovery of by-products for energy, production of inputs for other industries, and reduction of waste and pollution. A second critical aspect to the shift is that households may adopt multiple types of cooking fuels to serve their needs, a practice known as stacking.

Moving forward with the sustainable woodfuel agenda, let us not take for granted access to affordable cooking and heating fuel for the poor in SSA. We recommend that an improved and sustainable woodfuel system should be considered as an acceptable modern energy source under SDG 7.

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Data availability statement

All data that support the findings of this study are included within the article.

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