

Exploring lessons from five years of biochar-producing cookstoves in the Kagera region, Tanzania

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ARTICLE INFO

Article history:

Received 2 March 2022

Revised 5 September 2022

Accepted 17 September 2022

Available online xxxx

Keywords:

Biochar

Improved cookstoves

Agricultural residues

Soil amendment

Negative carbon dioxide emissions

Tanzania

ABSTRACT

Biochar-producing cookstoves can supply fuel-efficient heat for cooking in developing countries. The produced biochar can be used as a soil amendment, providing a range of environmental and agronomic benefits and serve to remove carbon dioxide from the atmosphere. Despite these advantages, many stove initiatives have not been sustained in the long term, but very little attention has been devoted to understanding the reasons behind this. The present study contributes to filling this knowledge gap, by identifying key factors affecting the level of stove adoption and use, as well as biochar utilization. Based on a follow-up survey of 50 households in north-western Tanzania that received microgasifier stoves in 2015, only 12 still made use of their stove 5 years later. One of the main reasons for this relates to the inadequate quality of stove material. Declining or inconsistent availability of feedstocks was also identified as a major challenge. Furthermore, the households generally did not embrace the idea of amending soils with biochar, due to a combination of local practices and perceptions, and a lack of education and awareness programs. We conclude that, under the conditions of the studied project, three factors are required to scale dissemination: improvement of the stove design, provision of training programs on biochar management and subsidies or microloans that would make more durable stoves affordable. Sustained stove deployment can only be achievable by institutionalizing financing structures that are independent from short-term grant-based initiatives.

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Introduction

The discovery of the exceptionally fertile terra preta soils in the Amazon basin was the first indication of the use of biochar as a soil enhancer (Glaser et al., 2002; Sombroek, 1966). Biochar is a carbon-rich material produced when biomass (feedstock) is heated between 300 °C and 800 °C under anoxic or oxygen-limited conditions (pyrolysis) (Tomczyk et al., 2020). Due to its agronomic benefits and role in climate change mitigation, the perceived value of biochar has grown among researchers, environmental experts, and policymakers during the last decade.

The Intergovernmental Panel on Climate Change (IPCC) recently included biochar as a promising negative emissions technology in its Special Report on Global Warming of 1.5 °C (de Coninck et al., 2018). The

application of biochar can increase soil carbon storage and net carbon dioxide removal from the atmosphere by i) acting as a carbon stock that persists for a long period of time once added to soil (Lehmann et al., 2015), ii) reducing the rate of soil organic matter decomposition for several years after application (Wang et al., 2016), and iii) augmenting plant production (Kammann et al., 2015) and potentially increasing carbon input to soil in the form of plant residues. From an agronomic perspective, biochar can enhance nutrient and water availability by improving the chemical and hydraulic properties of the soil (Glaser & Birk, 2012; Lehmann & Joseph, 2009). In addition, it can increase the activity of soil microbial communities (McCormack et al., 2013) as well as root symbionts, such as arbuscular mycorrhizal fungi, leading to increased phosphorus availability for plants grown under conditions of low phosphorus (Hammer et al., 2014, 2015).

Several biochar production technologies are used in rural areas of the Global South. Traditionally, earth mound or earth-covered pit kilns are most commonly used. More advanced technologies include retort

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kilns, such as the Adam retort kiln, and vertically placed top-lit updraft (TLUD) kilns. The latter can be designed for use as cookstoves. TLUD gasifier cookstoves are classified as improved cookstoves (ICS), i.e. a pyrolytic stove that produces combustible gases burned to generate heat for cooking, while producing biochar as a by-product. Thus, the agricultural use of biochar derived from ICS in homegardens in the Global South can contribute to negative carbon emissions, as well as resulting in additional agronomic benefits (Sundberg et al., 2020).

In recent decades, a number of government institutions and non-governmental organizations (NGOs) in Kenya and Uganda have worked together to promote the adoption of cleaner cooking solutions (Hewitt et al., 2018). Vigolo et al. (2018) argued that biomass will continue to be the most viable cooking fuel in the foreseeable future, due to that access to energy infrastructure and other cooking options remaining limited in certain regions. Wood and wood-derived charcoal are used for cooking by 70 % of the population of Africa and, notably, 90 % of Tanzania's population (Peter & Sander, 2009; Taylor & Nakai, 2012). Africa is the continent that experiences the largest net forest loss in the world (FAO, 2020). Promoting use of ICS may serve to reduce the need for firewood, and therefore help mitigate deforestation and forest degradation. In addition, reducing indoor air pollution offers a possibility to both reduce short-lived greenhouse gases and health risks associated with energy use in low- and middle-income countries (WHO, 2016).

To tackle these issues, grassroots initiatives in Tanzania have started introducing ICS to small households, with the aim of transitioning from traditional energy sources, such as open fires, to more sustainable cooking. At least three such projects have been initiated: stove engineer Bjarne Laustsen's project introduced pellet-burning microgasifier stoves (Jiko Bomba stoves), TREE Ltd. introduced pellet-burning microgasifier stoves via a project operating in Arusha (Lotter et al., 2015), and the 'Efficient Cooking in Tanzania' (EfCoiTa) project introduced TLUD and sawdust microgasifier stoves in Karagwe (Krause, 2019). The latter is the project followed up in the present study.

The EfCoiTa project, initiated in 2014, was the result of a collaboration between the Tanzanian NGO Community Habitat Environmental Management (CHEMA) and Engineers Without Borders Germany. Its aims were: i) to meet the demand of local smallholder communities for sustainable cooking technologies by providing ICS, ii) to decrease negative environmental impacts including deforestation, by alleviating the demand for firewood, and iii) to sustain and, if possible, improve crop production by using biochar as a soil amendment, leading to food security and increased incomes (Krause, 2019). The project focused on two types of ICS in the form of microgasifier cooking stoves that produce biochar as a by-product of gasification. Due to limited financial resources, follow up on the stove usage and collection of the users' feedback were not possible until this study.

To achieve the desired human health, climate, socioeconomic, and environmental benefits promoted by most ICS programs, the stoves must be acquired, used correctly and, importantly, used consistently (Chalise et al., 2018; Stanistreet et al., 2019). To fully benefit from sustainable deployment associated with ICS, sustained use of the ICS is a critical performance parameter, which deserves as much attention as does the technical stove performance (Ruiz-Mercado et al., 2011). A number of initiatives have been employed by civil society organizations to scale up use of ICS; however, most have not been able to fund and complete a follow-up program (Rehfuess et al., 2014). Experience from Tanzania indicates that focus has primarily been on boosting the manufacture and dissemination of several ICS prototypes, with much less effort on ensuring that stoves are used consistently (Massawe, 2019). Consistent use of the ICS entails accepting the technology at the household level and, consequently, replacing traditional stoves.

Unfortunately, little effort has been invested in understanding the mid- and long-term adoption and use of ICS (Hanna et al., 2012; Pillarissetti et al., 2014). With some exceptions (e.g. Jürisoo et al., 2018 and Ruiz-Mercado et al., 2013) that focus on the sustained use of

cookstoves, most studies have focused on measuring adoption of ICS based only on user installation or purchase of the stoves. There is a need for assessment of sustained use of ICS that goes beyond stove uptake. The questions of how well the ICS are adopted and maintained over time, and how the stove by-product, i.e. biochar, is utilized, remain unanswered.

The present study aims to contribute to filling these knowledge gaps by following up on the EfCoiTa project 5 years after microgasifier stoves were disseminated to small households in Kagera, Tanzania, and assessing ICS adoption and use, as well as the utilization of produced biochar.

Methods

Study area

The area for the study includes the Karagwe and Kyerwa districts in the Kagera region in northwest Tanzania, west of Lake Victoria (Fig. 1). Data were collected from the Kayanga, Ihanda and Nkwenda wards (Fig. 2).

Kagera has a tropical savanna climate; it is characterized by a distinct bimodal rain pattern (March–May and October–November), with rainfall varying between 500 and 2000 mm per year, while the mean temperature ranges from 20 °C to 28 °C during the day (Tanzania, 2012). According to Batjes (2011), the local soil can be classified as Andosol. Agriculture is the primary occupation of >90 % of the population in western Tanzania (Whitaker, 2002), and land in the Kagera river basin is to a very large extent influenced by human activities, with 60 % of the land surface being used for farming (Wasige et al., 2013). Approximately 400,000 to 500,000 households in the Kagera region are engaged in agriculture, and the majority of farmers in the area of study are smallholders (Reetsch et al., 2020; Tanzania, 2012). Furthermore, it has been one of the fastest growing rural regions in Tanzania (Tanzania, 2012), largely due to the influx of immigrants from Burundi, Rwanda, and the Democratic Republic of Congo after 1993 (Whitaker, 2002).

The EfCoiTa project

The EfCoiTa project was conducted in three phases between June 2012 and October 2015. In the first phase, a survey was conducted on 24 households in Karagwe to collect data on cooking habits, as well as biomass availability and use. In the second phase, two types of ICS utilizing different types of feedstocks were developed: a TLUD microgasifier stove that operates with pieces of firewood or maize cobs, and an improved sawdust microgasifier stove that uses sawdust or coffee shells. The third stage involved evaluation of the fuel consumption and emissions of ICS through a series of controlled cooking tests and measurements (Krause & Rotter, 2017). The distribution of the stoves to households took place in 2015. In total, forty households in the Karagwe district and ten in the neighboring Kyerwa district were provided with the stoves. Despite initial plans to charge a small fee for the stoves, they were eventually distributed to the households for free.

Study design

In the present study we provide a comprehensive assessment of the households' experiences with microgasifier stoves (TLUD and sawdust) 5 years after their distribution. For this purpose, we conducted a household survey and a workshop, through which quantitative and qualitative data were collected, respectively.

Due to the onset of the COVID-19 pandemic, the data were collected in cooperation with the local NGOs CHEMA and Women and Men for Destined Achievements (WOMEDA), who provided field assistants. WOMEDA is a grassroots NGO based in Karagwe, which promotes the status of marginalized groups through the provision of socioeconomic, legal, and human rights activities. The process of taking on NGO field



Fig. 1. Map of the study area with world map reference.

assistants resulted in additional communication being needed around metadata observations made while collecting the survey data.

Between March and May 2021, survey responses were collected from 50 households that had received a microgasifier stove. A total of 20 households that did not receive any technology from the project were also included in the survey as a control group (Table 1). Since TLUD and sawdust stove work with the same principle that involves the gasification of biomass into combustible gases and char and since stoves were received by the households within the same project frame at the same time, we decided to not analyze the two stove types separately. Moreover, separating the stove types will result in very few households in the TLUD households (only 10 households) which might affect the analyses. Thus, in this study we decided to

treat the TLUD and sawdust as one stove type referred to as microgasifier stove.

A primary objective of the EfCoiTa project and other similar initiatives is a reduction in the use of traditional stoves, such as three-stone cooking fires and charcoal burners. Therefore, comparing the use of cooking equipment, including traditional stoves, between the groups was key to understand the long-term impact of ICS interventions.

Survey design and response analysis

A modular questionnaire was produced so that different versions could be used according to the group being interviewed (Appendix A. Supplementary data). Since the households of the control group did not receive microgasifier stoves, they were provided with fewer

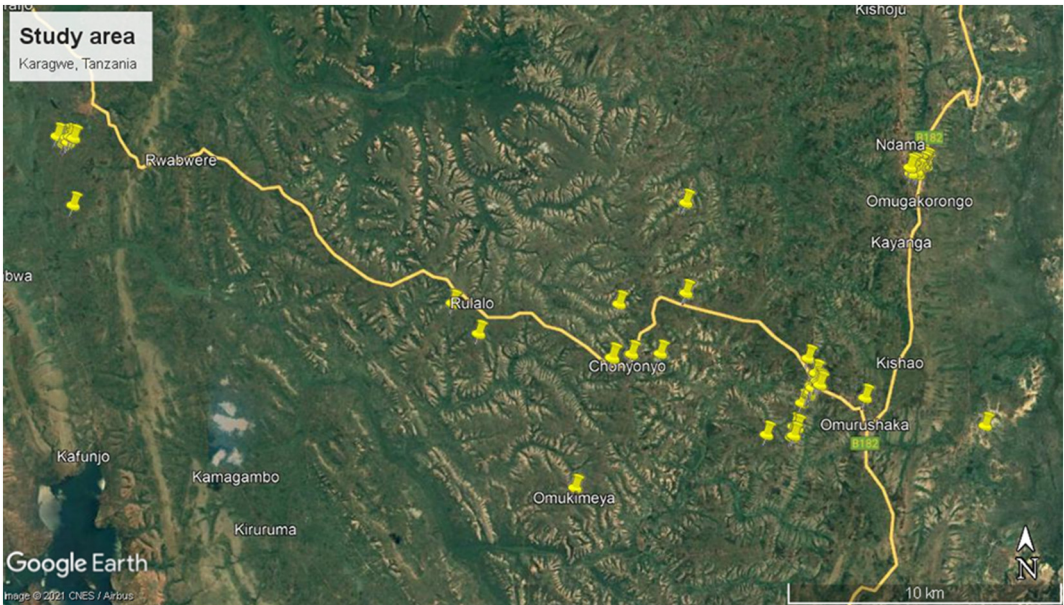


Fig. 2. Map of locations of the interviewed households.

Table 1
Households that responded to the survey.

Respondent group	No. of households surveyed	Technology received
Stove group	50	Either TLUD or sawdust stove
Control group	20	No technology

questions, while the beneficiaries of the technology were asked about the use of their stoves and its by-product. Data on demographic characteristics, cooking behavior, cooking energy sources, household waste management (including the stove by-product biochar), farm management, and soil inputs were collected from all households.

We aimed to study the impact of the intervention by comparing groups with relatively similar demographic characteristics, and to indicate any socioeconomic factors that might affect the household cooking behavior. Differences between the groups were evaluated using Student's *t*-test for continuous variables, and the chi-squared test for discrete variables. A Likert-type response format was used to assess attitudes towards the microgasifier stove technology on a bipolar scale ranging from 'strongly agree' to 'strongly disagree', with 'undecided' as the middle option. For questions on behaviors, we used either five alternatives of responses on frequency (always, often, sometimes, rarely, and never) or six (every day, 3–5 times per week, 1–2 times per week, 1–2 times per month, and never), accordingly.

Workshop discussion and outputs

In November 2021 we organized a full-day online workshop with participants from CHEMA and Engineers Without Borders Germany to share and discuss the findings from the survey and to gather deeper insights into the use of microgasifier stoves in Karagwe and Kagera. The workshop program consisted of presentation of the survey data to the participants, and time for discussion and questions. The participants' comments were collected by the workshop facilitators and summarized on a virtual whiteboard that was accessible to all participants.

By discussing the survey results in a workshop, we were able to gain deeper perspectives into certain aspects of the quantitative data that were hard to capture. The workshop method helped to increase our understanding of the results and provided clarifications on several aspects, e.g., by highlighting certain cases where the stoves were left completely unused, by providing suggestions on design details that could improve the stove, and by explaining local variability of feedstock supply and logistics.

Despite restrictions and travel bans caused by the COVID-19 pandemic, the study was completed successfully, due to the strong partnership between the NGOs and our research team, as well as past on-site collaborations in Karagwe.

Results

Demographic characteristics

Our study includes data from 70 households: 50 in the microgasifier stove group and 20 in the control group. Of the 50 households that had received microgasifier stoves from the EfCoiTa project in 2015, 3 could not be located for follow-up, and were replaced with 3 households that received stoves from the EfCoiTa project more recently (after 2017).

A summary of the demographic characteristics of the two groups is listed in Table 2. Household sizes were similar between the two studied groups and ranged from 1 to 10 persons, with a mean of 5 members. Women represented 50 % and 92 % of the interviewees in the control and stove groups, respectively – we aimed to interview as many women as possible in this follow up, since they are more involved in cooking and kitchen tasks than men in the areas in question.

Almost all households owned their farms; only 1 household (2 %) of the households in the stove group were leasing their farm.

Table 2
Household demographic characteristics.

Variable	Control group (n = 20)	Microgasifier stove group (n = 50)	t/ χ^2	p-Value
Household size ^a , n	4.6 ± 1.6	4.6 ± 1.4	0.000	1.000
Sex of respondent ^b , %			17.750	>0.001
Male	50	8		
Female	50	92		
Primary occupation ^b , %			0.824	0.364
Farming	100	96		
Livestock	0	4		
Casual labor	0	0		
Business	0	0		
Farm status ^b , %			0.824	0.364
Owned	100	98		
Leased	0	2		

^a Continuous variable described in mean and standard deviation; Student's *t*-test (t).

^b Discrete variable described in proportions (%); chi-square test (χ^2).

Energy sources for cooking and use patterns

This section presents the results regarding the different types of stoves owned by the households, the frequency of use of each stove type, and the share of use in cooking.

Categories of cookstoves owned by the surveyed households

At the time of the interviews, all households owned multiple kinds of cooking equipment, fueled by different sources of primary energy. These included basic three-stone cooking fires, charcoal burners, microgasifier stoves, liquefied petroleum gas (LPG) stoves, and electric stoves. The survey response analysis revealed that the three-stone cooking fires and charcoal burners remained the most commonly owned cooking equipment in the surveyed households in both groups. Approximately 8 % of households in the stove group and 5 % in the control group owned an LPG stove, and electric stoves were the least common type of cooking equipment, found in only 1 control household. All households in the stove group still owned either a TLUD or a sawdust stove received from the EfCoiTa project, while none of the control households possessed such a stove (Fig. 3). In the Results section, the term microgasifier stove includes both the TLUD and sawdust stove.

Frequency of use of each stove type

The representatives of the surveyed households were asked how frequently they used each of the cooking technologies they reported owning (Fig. 4). Among the owners of microgasifier stoves, 18 % stated that they used the stove every day and 6 % used it 3–5 times a week. Notably, 76 % reported that they never used the stove. The technology used most frequently was the three-stone fire: 80 % of those who owned a

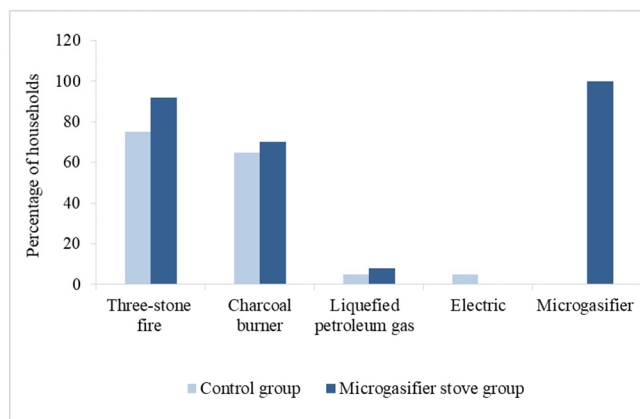


Fig. 3. Types of cookstoves owned by the surveyed households.

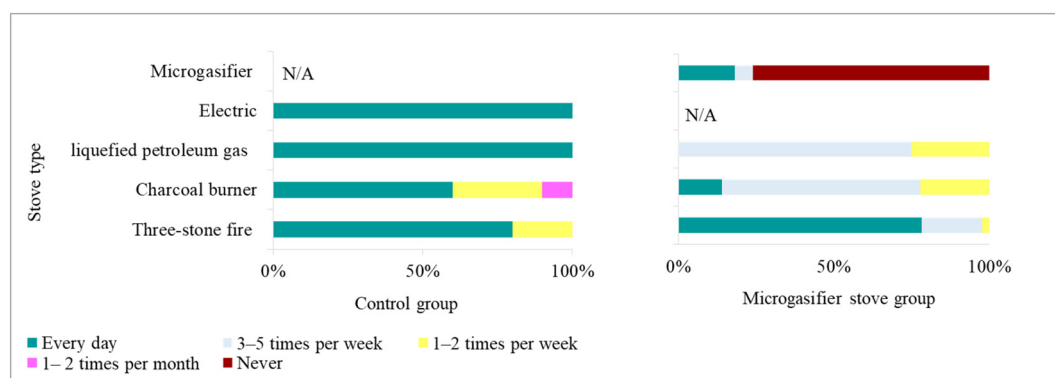


Fig. 4. Frequency of use of each stove type.

three-stone fire used it for cooking daily. Of the households in the stove group that owned a charcoal burner, the majority (77 %) reported using it every day or 3–5 times a week. However, this type of stove was used less regularly than in the control group, particularly by the households that stated frequent use of the microgasifier stove. In the control group, approximately 60 % of the charcoal burner owners used it every day, while 15 % made use of it twice a week and 5 % once or twice a month. Although LPG stoves were not commonly owned among the surveyed households compared with the other cooking equipment, they were being used with relatively high frequency. All owners of LPG stoves in the microgasifier stove group stated using it at least twice a week, while all those in the control group reported daily use. An electric stove was owned by a single household in the control group and was being used every day. Overall, the data indicate that the households in the stove group were continuing to rely on the traditional stoves for cooking more than on the microgasifier stoves in their possession.

The lack of dissemination of the microgasifier stoves to the control group is clear (Figs. 3 and 4). This observation was confirmed in the workshop discussion with members of the local NGOs; however, according to their information, a small number of households that were not part of the initial project have indeed adopted the technology, but were not included in this study.

Benefits and challenges related to the microgasifier stove

Here we provide results on the microgasifier stove feedstock, lifespan, user perceptions, and utilization of produced biochar.

Microgasifier stove feedstock

Overall, different feedstocks were being used by the surveyed households to fuel their stoves (Fig. 5). These were often types of household waste or were sometimes purchased from local fuel shops. The most commonly used feedstock sources among all stove owners were powdery sawdust (30 households) and coffee husks (18 households). Only 6 households used maize cobs, while 9 used firewood. Among the stove owners who stated that they were using their microgasifier stoves at the time ('current' stove users), the most used feedstock was powdery sawdust (7 households) followed by firewood (3 households) and coffee husks (2 households). At the time of data collection, maize cobs were not being used as feedstock by any current stove users.

During the workshop discussions following the survey response analysis, it became clear that the feedstock variability among different areas in the study region was large. At the time of collecting the survey data, maize cobs were not being used to fuel the stoves, likely due to their unavailability during certain parts of the year. Where there were large areas of forest, firewood was readily available, and the incentive to use residues such as sawdust from sawmills and from agriculture was therefore low. However, CHEMA reported that many households considered the work of cutting firewood into smaller pieces to be laborious, the price of firewood and charcoal was high (and rising) compared with that of sawdust, and existing systems were in place for delivering bags of sawdust to households. Furthermore, CHEMA had received a briquette-maker (bought by the local government) for processing sawdust, the supply of which CHEMA considered stable. This could facilitate logistics by enabling easier transport and simplifying the method of feeding the material into the stoves. Another type of



Fig. 5. Types of feedstocks used to operate the microgasifier stoves by all stove owners (left) and the current stove users (right).

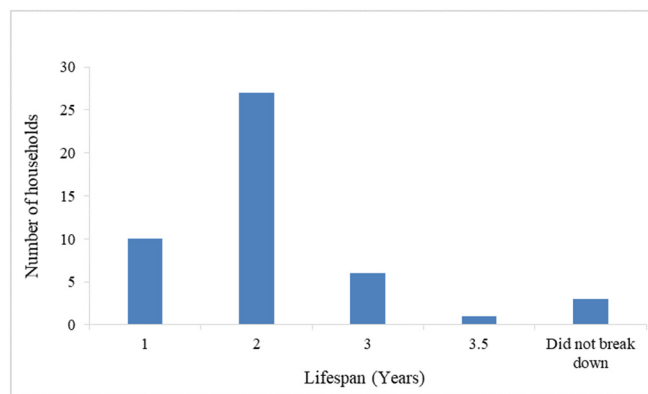


Fig. 6. Lifespan of the microgasifier stoves.

feedstock mentioned by the stove users were coffee husks, which had previously been available from a factory within the study area; however, the factory burned down, and, after reconstruction, the coffee husks were sold to other buyers rather than costumers at the local market. This highlights the variability of the supply of local biomass, and partly explains why those who were using the microgasifier stoves preferred to keep a range of cooking equipment that used various energy sources with fluctuating availability, particularly three-stone cooking fires, rocket stoves and charcoal burners. This inconsistency in feedstock availability may favor stove designs that are flexible with regards to feedstock input. On the other hand, due to its relatively stable supply and ease of use, sawdust could be a preferred feedstock, and its local availability could encourage the adoption and dissemination of microgasifier technology. Sawdust supply chains to users of microgasifier stoves should be of particular interest to future projects. For instance, sawdust briquetting may increase the demand for microgasifier stoves, but the price of a briquetting machine, which starts at around €10,000, is not affordable for most grassroots initiatives. Ultimately, locally produced rocket stoves – another type of ICS not included in the study, and not mentioned by interviewees – can take different feedstocks, such as firewood of various sizes, briquettes and maize cobs. CHEMA is the main producer and distributor of rocket stoves in Karagwe district (Krause & Rotter, 2017).

Lifespan of the microgasifier stoves

Fig. 6 displays the lifespans of the microgasifier stoves disseminated between 2015 and 2017 as part of the EfCoiTa project. The survey revealed that 70 % of the stoves (35 out of 50) broke down within 2 years. After breaking down, 4 households replaced the stoves with new ones, while 10 households repaired them, mainly at welding shops (one owner repaired the stove themselves). The rest of the stoves were left broken and unused. However, after reparation, 5 stoves broke down again. Many users lacked motivation or were reluctant to repair

their broken stoves, as they perceived the short lifespan of the stoves as a drawback, and appropriate feedstocks were not easily available to them. As one survey respondent noted, “After missing out coffee peels, I didn't see the importance in repairing the stove” pointing to stability in feedstock supply as an important factor in ICS program success. Among the 50 stoves distributed, only 3 did not break down in the 5-year period since they had been received.

During the workshop, one of the likely reasons noted for the longer lifespan of the 3 stoves that had not broken down between 2016 and 2021 was that certain households did not use their stoves frequently.

According to the CHEMA stove technician, the stoves were breaking down because certain exposed parts were corroding and weakening the structure, partly due to the thin (1.2 mm) metal sheets used in the stove design. The possibility of using thicker and/or galvanized steel sheets was discussed with the stove technician during the workshop: it would be possible to construct the exposed parts using more expensive material; however, using thicker sheets (2.0 mm) or galvanized steel would double or almost triple the cost of production, respectively. The cost of an ICS is often the primary reason for not switching to sustainable cooking energy sources. This is commonly due to the households' purchasing power, particularly in lower-income communities. In the present survey, the cost of buying the stove was not reported as a barrier by the respondents, since the stoves were donated by CHEMA as part of the EfCoiTa project. On the other hand, repair costs would be borne by the households themselves, making it a challenging task. It is possible that the prolonged lifespan of stoves built with thicker or galvanized steel would make up for the increased production cost; however, there is a lack of investment capital in many rural Tanzanian areas. The average household cannot afford more expensive products, even if the investment made sense in the long term, and local NGOs lack the capital to invest in better quality materials and tools to improve the manufacturing process. We have previously identified lack of capital as a key barrier to biochar deployment in Tanzania (Fridahl et al., 2021).

Users' perceptions around benefits and challenges related to microgasifier stoves

When asked about the merits of the microgasifier stove, most of the stove owners (88 %) either strongly agreed or agreed that they were more beneficial than traditional stoves in terms of fuel-saving ability, reduced smoke and unwanted heat, emissions, and ease of handling (Fig. 7).

More specifically, 94 % of the respondents strongly agreed that fuel saving was an advantage. The same number of respondents strongly agreed or agreed that the stove produced less smoke than traditional cooking stoves. Regarding operation, the majority of the respondents (84 % of the respondent) answered that the stove was easy to handle. Almost half of the stove owners agreed that the ability to use biochar as compost additive was an advantage of the stove, while the remaining respondents were undecided or disagreed.

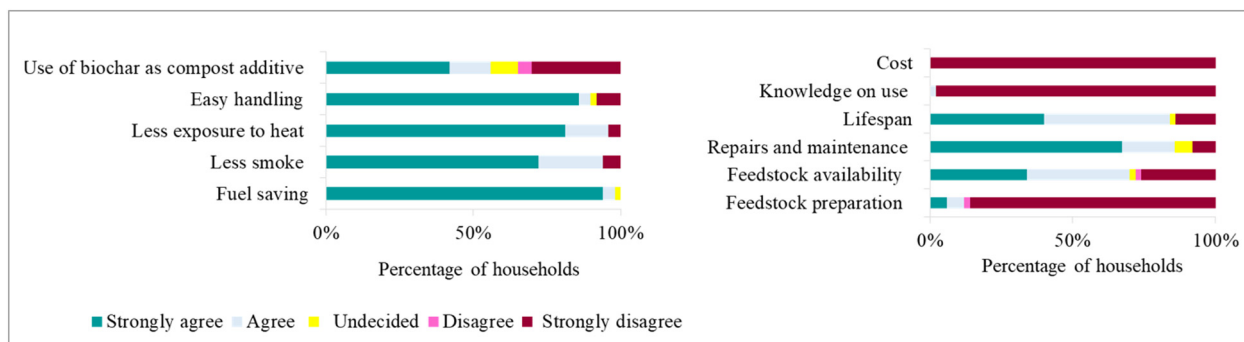


Fig. 7. Users' perceptions of benefits (left) and challenges (right) related to microgasifier stoves.

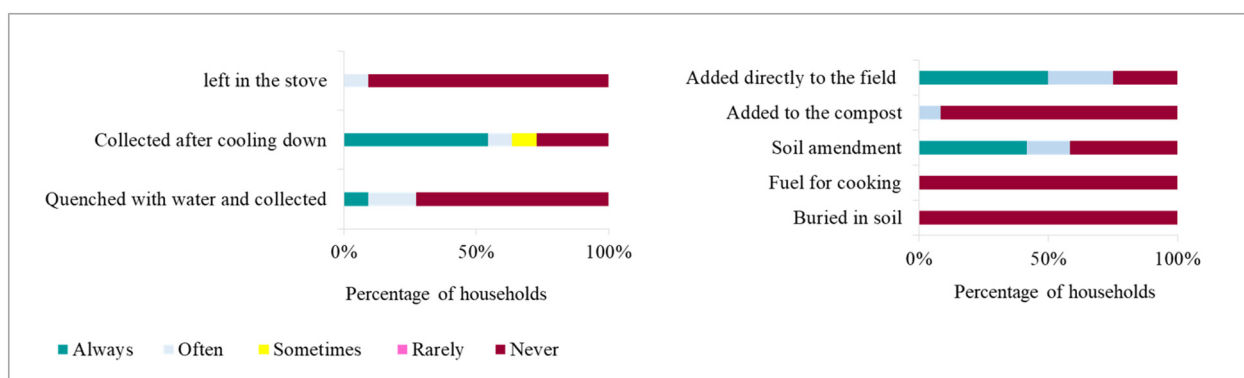


Fig. 8. Collection (left) and use (right) of the produced biochar among the users of microgasifier stoves.

Regarding the challenges of using the microgasifier stove, no household reported cost as a disadvantage, as they had obtained them for free. Similarly, only 6 % of the respondent households reported that the knowledge on use as a challenge. Repairs and maintenance were the primary drawbacks noted (66 % of the stove owners strongly agreed). The short lifespan of the microgasifier stoves and the lack of availability of feedstock (discussed above) were perceived as challenges by 88 % of the respondents and 70 % of the respondents, respectively. In contrast, the preparation of the feedstock was not considered a problem overall, as only 12 % of the respondents strongly agreed or agreed that this was a challenge.

Utilization of the biochar by-product

According to the responses of the study participants, the mean amount of recovered biochar from a microgasifier stove was found to be 3 L/day per household (range, 0.5–5.0 L/day per household). After cooking, the produced biochar from the stove was collected either after immediate quenching with water, after it had cooled down, or the following morning (Fig. 8). Among the current stove users, the majority (8 households) tended to collect the biochar from the stove after it had cooled down, while 3 households quenched the biochar directly after cooking and collected it. Only 1 household left the biochar inside the stove until the following day.

The average recovered biochar of 3 L/day per household is estimated to be equivalent to approximately 1.5 kg/day per household. We assumed a density of 0.5 kg/dm³, based on [Brewer et al. \(2014\)](#), who reported a biochar density range of 0.25–0.60 g/cm³, with higher values for biochar from wood sources, and [Krause and Rotter \(2018\)](#), who estimated a daily recovery potential of 0.2–0.5 kg per household from microgasifier stoves in which residues were not quenched after cooking, but were left until the following day, resulting in a continuation of the char residue oxidation to ash.

Regarding the utilization of the recovered biochar among the current users, we found that the biochar was mainly being added to soil without treatment (Fig. 8): users either placed it directly into their field, or around plants as soil amendment. Only 1 household reported adding the produced biochar to compost (composted biochar).

Table 3 indicates the average quantity of biochar determined to be produced annually per household. The content of carbon, nitrogen and phosphorus was calculated according to published data on biochar and ash recovery from microgasifier cookstoves ([Krause & Rotter, 2018](#)).

Table 3

Nutrient recovery potential of biochar produced from cooking stoves per household per year.

Element	Recovery potential per 547 kg biochar, kg
Carbon	410
Nitrogen	1.6
Phosphorus	1.0

Discussion

The present study followed up on beneficiaries of the EfCoITa project in Tanzania, revealing that only a small number of households that were provided with microgasifier stoves during this initiative were still using them 5 years down the line. Several key factors served a role in limiting the long-term use of the microgasifier stoves: the stove lifespan, along with relevant repairs and maintenance, as well as the availability and quality of feedstock.

Challenges around the sustainable use of the microgasifier stove as a cooking energy source

Our results highlight the short lifespan of the stoves being a key reason for 70 % of households to have discontinued using their stove after 2 years. Accordingly, a positive relationship between the gasifier stove durability and its continued adoption was reported in a cross-sectional study conducted among 5830 households in rural Ethiopia ([Adane et al., 2020](#)). Our investigation revealed that the short lifespan of the stoves developed by CHEMA was due to a technical setback, whereby the frequent use and high temperatures to which it was exposed were causing deterioration of the fuel chamber after 1–2 years. A similar issue was reported for another project, the Trans-SEC initiative (Innovating Strategies to Safeguard Food Security Using Technology and Knowledge Transfer – A people-centered approach) in Morogoro Region, Tanzania. In the Trans-SEC project, the biochar-producing TLUD kiln was wearing out, and its maintenance was considered expensive. The researchers identified technical problems and the lack of investment capital as key barriers to continuing similar initiatives ([Fridahl et al., 2021](#)).

In the present follow up study, the lack of feedstock availability was identified as a major challenge for frequent stove use. This is in line with a study conducted in Malawi, which reported a lower interest in ICS adoption from households that had a smaller share of crop residues as a fuel supply ([Jagger & Jumbe, 2016](#)). Our qualitative data indicate that the supply of local residual biomass that were being used as fuel for the stoves (such as coffee husks or maize cobs) was often inconsistent, affected by events such as the destruction of the local coffee factory by a fire, and the seasonal variability of access to maize cobs. This explains why many households continued using a three-stone fire for cooking alongside the gasifier stove, an approach referred to as 'stove stacking'. Indeed, the practice of utilizing more than one stove type to fulfil cooking needs has been reported previously for rural households in, e.g., Ghana, Kenya, Nigeria and Mexico ([Jewitt et al., 2020](#); [Ochieng et al., 2020](#); [Piedrahita et al., 2016](#); [Serrano-Medrano et al., 2019](#)).

Certain similar studies have reported that fuel preparation, such as cutting wood into smaller pieces, was considered as a challenge for using a gasifier stove, since this is additional to what is needed to prepare a three-stone fire ([Gitau et al., 2019](#)). By contrast, most of the

respondents to our survey did not identify this as a challenge, particularly compared to the availability of the feedstock itself. However, a small number of respondents mentioned that preparation of feedstock is tiring work for them in general, due to their age.

Cost is often identified as a key barrier to adoption and/or repurchase of a high-quality ICS (Rehfuess et al., 2014). The households included in our study did not purchase the stoves, as they were provided for free by CHEMA, explaining why the respondents did not generally consider the price of the stove to be a deterring factor in the first instance. Yet, cost would likely be the main challenge for repurchasing the stove, particularly with the absence of a subsidies system. Notably, Krause (2019) found that the local price for a microgasifier stove was comparable to that of good quality charcoal stoves, but certainly more expensive than a simple charcoal stove. To overcome the challenge of cost, provision of funds for investment in ICS is important, not only for adoption, but also for dissemination. This could be achieved through government financing, foreign aid programs, research grants, or startup financing to cover stove costs and provide subsidies. Biochar-producing cookstove initiatives could attract foreign funding under the context of climate change mitigation, by being promoted as carbon sequestration projects. Along with sequestering carbon, biochar has additional low-cost co-benefits, such as improving soil fertility and crop productivity (Krause et al., 2016; Lehmann et al., 2006; Scholz et al., 2014).

A strong dependency on external grant financing, such as research grants, startup financing, or development aid, is considered a threat to the continuation of initiatives like the EfCoITa project in Tanzania, and several studies have reported that such initiatives ended soon after termination of external funds, when the practitioners failed to fully cover operational costs (Fridahl et al., 2021; Hansson et al., 2021; Rogers et al., 2022). There are several ICS programs in sub-Saharan Africa that have been or are relying on revenues both from regulated and voluntary carbon markets. These projects are financed based on their contribution to reduced use of non-renewable woody biomass and fossil fuels for cooking (Hewitt et al., 2018; UNFCCC, 2012). Although it may be possible to finance biochar-producing cookstoves based on their ability to reduce emissions, the carbon sink provided by biochar has not – to the best of our knowledge – been included in standards that determine the possible climate benefit from ICS programs. For monitoring and verification, biochar production from households would have to be extensively surveyed since the amounts of biochar received from the stove can vary depending on operating practices. In addition, the trade-offs between the use of biochar as a soil amendment on the one hand, and as a fuel on the other would require rigorous testing and potentially monitoring technology not available to ICS programs in least developed countries (Hansson et al., 2021). Furthermore, it has been observed that some biochar actors in Tanzania are reluctant to link their projects to carbon markets (Fridahl et al., 2021).

Challenges of using biochar as soil amendment

According to the surveyed users in the present study, the microgasifier stove fulfilled their expectations, which were based on how it had been promoted by the EfCoITa project. However, the value of the produced biochar was not as readily accepted, although 48 % stated that they associated biochar with benefits. This is likely due to the use of biochar not being included in the educational program provided by EfCoITa on how to operate the stoves. Adding biochar to the soil can be a social barrier, as it is an unfamiliar practice for many local farmers (Hansson et al., 2021), ash is associated with causing thunderstorms (Reetsch et al., 2020) and there are cases of adding biochar to soil being considered witchcraft (Rogers et al., 2022). There is therefore a clear need to communicate the difference between ash and the biochar produced by microgasifier stoves. Other factors that may contribute to the poor implementation of biochar as soil amendment in similar settings are: limited access to capital, lack of enabling policies,

lack of awareness, and insufficient access to experts and knowledge (Rogers et al., 2022).

According to the collected data, we estimate that an average of 547 kg biochar, containing 410 kg total carbon, can be recovered from the stove of each household annually. Application of this amount of biochar in homegardens as soil amendment is valuable as a means of soil carbon sequestration. Recent study data support this use of biochar to store carbon in soils. For example, Blanco-Canqui et al. (2020) reported that maize field plots treated with 9300 kg/ha biochar in 2011 contained 11,820 kg/ha more soil carbon in their upper 30 cm in 2017 than plots that had not been treated with biochar. The authors suggested that biochar can increase soil carbon stocks directly and through negative priming (the reduction in mineralization of native soil organic matter and/or fresh crop residues). Due to its relatively recalcitrant organic compounds, biochar has the potential for long-term stability in the soil (Lehmann & Joseph, 2009). In the context of our study, the local soil (Andosol) in Karagwe has the potential to act as carbon sink. This is because the great ability of the Andosol to accumulate organic and to protect organic matter from degradation through forming either metal-humus or allophane-organo complexes (Zakharova et al., 2015).

However, the impact of biochar on soil carbon depends on several factors, such as the feedstock material, the pyrolysis temperature, and the soil physicochemical characteristics (Ding et al., 2018). Moreover, in Andosols of Karagwe, alteration in soil carbon after biochar application was not detected over the course of a single cropping season after the application as reported by Krause et al. (2016). Thus, long-term biochar field trials in Karagwe, using biochar produced from the homegardens, are needed for a more accurate estimation of the benefit to the soil.

We observed that, out of the 12 households still using their microgasifier stoves at the time of follow up, 11 were adding biochar to their soils without treatment, and 1 was mixing it with compost. However, mixing biochar with other organic, nutrient-rich material, such as kitchen waste and harvest residues, prior to soil application has been found to be the most efficient way to reap the benefits. This is due to the large surface area of biochar (resulting from its extremely porous structure), which allows adsorption of nitrogen and phosphorus (Kammann et al., 2015). Our findings therefore reflect the need for education and training regarding the treatment of biochar before application to soil. During the workshop discussions of this study the project initiators revealed that biochar could be used locally for cooking in available stove designs that utilize charcoal after the initial gasification. However, it was not observed in our study that biochar was being utilized as a cooking fuel rather than a soil amendment.

Conclusions

This study concludes that the long-term use of biochar-producing microgasifier stoves by households in the Kagera region of Tanzania has been inhibited primarily by the lifespan of the stove, the effort and cost related to repairs and maintenance, and the inconsistent availability of feedstock. Most of the stove users included in our study agreed that the benefits of these stoves include fuel saving, lower heat and smoke emissions, and easy handling; however, 70 % of the surveyed households were not able to use the stove beyond 2 years from receiving it. Our findings suggest that improving the stove design may extend its lifespan. Furthermore, we found that the use of biochar as soil amendment was not implemented by the respondents, mainly due to lack of awareness, highlighting the need for training programs and field demonstration activities to raise awareness around the agronomic and environmental benefits of biochar. Different forms of funding could be available to help tackle these issues and for scaling up the EfCoITa initiative. Although there is a need to move beyond the dependency on external financing, such funds are still needed for improving the stove design, implementing subsidies programs, and training. These activities would help achieve and sustain the socioeconomic, environmental, and health benefits of the EfCoITa project and other similar initiatives.

CRediT authorship contribution statement

Amna Eltigani: conceptualization, methodology, formal analysis, writing - original draft, visualization, project administration. **Alexander Olsson:** conceptualization, methodology, writing - original draft. **Baraka Ernest:** conceptualization, writing - original draft. **Ariane Krause:** scientific advice, conceptualization, writing and editing. **Mathias Fridahl:** methodology, conceptualization, writing - review & editing, supervision. **Anders Hansson:** funding acquisition, project administration, supervision, writing - review & editing. **Pius Yanda:** writing - review & editing, supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to acknowledge the vital input and feedback from Adelard Ndibalema CHEMA, Adam Bitakwate MAVUNO, Juma Masisi WOMEDA and Fabian Schmid at EWB.

Funding

This work was funded by the Swedish Research Council for Sustainable Development (Formas) within the National Research Programme on Climate “Visions and Conditions for a Fossil-Free Welfare Society” [Grant no. 2019-01973], and the Swedish Research Council (VR) and Sida through the Swedish Government's development aid funds and Formas' research appropriations “Sustainability and Resilience – Tackling Climate and Environmental Changes” [Grant no. 2016-06359].

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.esd.2022.09.015>.

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