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Original research article

Soils, sinks, and smallholder farmers: Examining the benefits of biochar energy transitions in Kenya

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ABSTRACT

Besides reducing fuel demands and indoor air pollution, pyrolytic cooking stoves produce a by-product (biochar) that can improve soil fertility and serve as a sink for carbon sequestration. Most smallholder farmers in Africa depend on wood for fuel, suffer from exposure to smoke and soils in their cultivated farms are deteriorating. Biochar (bio-charcoal) production has potentials to reduce energy requirement, diminish exposure to smoke, improve soil health and ease household activities traditionally associated with female labour. However, introducing new technologies and behaviours that tackle existing problems without creating new ones is a complex endeavour. Transitions need to be anticipatory, comprehensive and inclusive. Having this in mind, a transdisciplinary study was conducted from 2013 to 2019 with 150 households in three agro-ecological zones of Kenya. The socio-economic conditions, the uses of fuels and stoves, the crops grown and fertilizers used, as well as the labour division within households were documented. Selected households were given pyrolitic cooking stoves and trained in applying biochar to the soil. After two years of using the cooking stoves and applying biochar, studies were conducted to assess the feasibility and preliminary impacts based on the households own perceptions and experiences. The results showed that the strategy represented a viable option to deal with fuel use efficiency, exposure to indoor smoke and soil degradation, as well as easing the burden on female labour.

1. Introduction

Soil degradation, diminishing fuel sources and unhealthy cooking techniques are distinctive features affecting most poor households in rural Africa. Soil degradation and its numerous consequences are a global concern, but the impacts on African smallholders is a pressing matter [1–7]. Simultaneously, traditional fuel sources such as firewood, the dominant fuel-energy source in rural Africa, are becoming scarce in most parts leading to undesirable impacts on both people and ecosystems. In sub-Saharan Africa, woodfuels account for 60–95% of total national energy use [8–14]. Furthermore, the dominant cooking techniques in rural Africa have been associated with the negative health impacts, particularly on women and children [12,13,15–17]. The above requires innovative, healthier and more sustainable ways to produce and consume energy. We explored the strategy of using gasifier cooking stoves that reduce feedstock demands, minimize exposure to indoor cooking smoke and produce biochar for soil amendment purposes.

Biochar is the solid remaining that forms when organic matter is heated to high temperatures (sometimes exceeding 700 °C) under oxygen-deprived conditions. The final product is dominated by carbon forms and can be applied to improve soil productivity and store carbon [18–21]. Research on biochar's potential uses is gaining momentum [22–26]. Its impacts on soil fertility have been explained through chemical, physical and biological mechanisms. The effects on soil have been explained by the increase of the pH in acid soils [27], through cation adsorption [28], or by its impacts on soil biota [29]. However, results vary and more focused research aiming at local solutions is needed. Likewise, holistic approaches integrating the natural and the social are scarce. More emphasis has been put on the techno-economic dimensions than on the socio-cultural ones, leading to

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misunderstandings of the problems and opportunities at hand [22,30,31].

As biochar is also attracting the attention of public and private interests, competing discourses on the topic are emerging. Some argue for scaled-up systems while others favor smaller systems of production to ensure some degree of sustainability. While skeptics warn for a 'new' panacea to the complex problems of soil degradation and poverty in Africa [5,30].

This article aims (a) to describe the initial socio-economic conditions of these sites and (b) to present farmers' experiences after two years of producing and applying biochar. The results originated from a 2014 baseline study and follow-up studies carried out in 2018. The article starts by outlining the approach and the arguments behind it, as well as the materials gathered and methods used. Then it outlines the conditions captured by the baseline study, which were the socio-economic conditions in the areas studied, fuel and fertilizer uses, the availability of suitable feedstock for biochar production and the present uses of that feedstock. Subsequently, it introduces the follow-up studies, which comprise the perceptions of the participating households in relation to (a) the production and applicability of biochar and (b) the preliminary observed impacts on energy use, soil health and household economies. Lastly, it wraps up with a discussion integrating the meaning of these preliminary results and some concluding remarks.

2. The framework

Innovation and technological transfer can oftentimes challenge rationality, as the benefits they might bring to a socio-economic system do not always guarantee their acceptance. Successful technological transfers take into account specific cultural conditions [32–34]. Only holistic strategies including factors ranging from biophysical to socio-cultural ones, lead to genuine adoption [35].

Several variables were integrated into a system of analysis including feasibility of on-farm biochar production, impacts on fuel-use efficiency and soil fertility, potential economic and health outcomes. Once households obtain the gasifier[1], the process relies on resources available on-farm and immediate surroundings. Cooking and producing biochar become two sides of the coin, where the end-user controls the process by selecting fuel feedstock, cooks with it, produces biochar and applies it to the soil. This stands in contrast to buying biochar and depending on markets and uncontrolled origins. This was deemed central as the goal was toward a sustainable option of producing and using biochar with positive impacts on these communities and the environment.

Due to the complexity of the topic, the approach adopted was a transdisciplinary one and the research team included soil scientists, environmental engineers, bioenergy and social scientists working tightly with the end-users. In a broader project we captured the socio-environmental conditions, evaluated the technical aspects of on-farm biochar production, as well as its potential impacts [13,14,36–38]. During all the research process the team discussed, evaluated, included, and created awareness of how issues such as power relations, gender and language barriers might affect the quality of the data gathered [39].

3. Materials and methods

To test the feasibility of the strategy in dissimilar environments, sites with diverse agro-ecological characteristics were chosen (see Fig. 1). Likewise, households with varying socio-economic conditions and educational levels but fitting the category small-scale farmer were recruited (see Fig. 2).

As the methods and techniques used during the baseline and the follow-up studies vary, we choose, for pedagogic reasons, to present and explain these in due time and in connection to the discussion of the different interventions. Thus, the procedures of the follow-up studies are in Section 3.2 (data collection) but also retaken in results.

3.1. Site introduction

In line with the aforementioned diversity criteria, we carried out our studies in Embu, Kwale, and Siaya (see Fig. 1). In Embu, daily average temperatures range from 12 °C to 27 °C. The low temperatures during winter are attributed to the location of the county at the southeastern slope of Mount Kenya and its elevation, 1350 m above the sea level [40]. In a dissimilar landscape, we find Kwale with four major topographical features: the coastal plain, the foot plateau, the coastal uplands and the Nyika plateau. It has a monsoon type of climate and a daily average temperature of 24 °C [40], while Siaya has a modified equatorial climate. The average altitude of the county is 1140 m in the lowlands and over 1400 m in higher areas. This variation results in different temperatures. The daily average temperature is 30 °C during the hottest months and 21 °C in winter. The undulant topography is dissected by the rivers of Nzoia and Yala [41]. Annual rainfall varies, being the lowest in Kwale ranging from 400 mm to 1680 mm, between 1170 mm and 1450 mm in Siaya and averaging around 1495 mm in Embu.

Agricultural activities in these areas include tea, coffee and macadamia in Embu; cashew, coconuts and fruits in Kwale; groundnuts, kale and sweet potatoes in Siaya. As in most of Kenya, cultivating maize, beans and rearing livestock are common in these sites.

3.2. Data collection

In the data collection, quantitative and qualitative approaches were used. For the baseline study, two districts per county were selected, Embu North and Embu West in Embu; Siaya and Gem in Siaya; and Kwale and Matuga in Kwale. This choice was based on purposive and convenience sampling [42,43]. The purposive sampling aimed to guarantee variation in households (poor/less poor, close to/far from forests, male/female headed, numerous/less numerous, and so on). Village chiefs, local researchers and field assistants participated in this process. The convenience sampling's aim was twofold. First, we had long-term projects offering good knowledge of these localities and access to local field assistance. Second, households invited to participate had to agree to a certain level of engagement with the project. The 150 households chosen responded to a survey of 304 variables capturing demographics, socio-economic conditions, current fuel energy and stove uses, availability of feedstock suitable for biochar production and their present uses. Likewise, we mapped the current fertilizer uses, the crops grown and their marketization, along with the labour division within the household. In addition, we carried out semi-structured interviews with selected households and key informants, such as village chiefs and local researchers, on the need and suitability of the strategy. With few exceptions, all interviews were carried out in local languages with the help of field assistants but always with the presence of a senior researcher. The interviews lasted between 45 min and one hour. The data was analysed with the help of the "Miles and Huberman framework" going through the following stages: data reduction, data display and drawing and verifying conclusions [44].

For the households, the disposition to adopt the latter became prerequisite for further participation. In 2016 the stoves were introduced.

From January to August 2018, a series of follow-up studies were carried out in the three sites. These studies aimed at, firstly, giving the farmers feedback on the uses of the stoves and application of biochar

[1] The gasifier used in this study is Top-Lit UpDraft (TLUD) gasifier cookstove branded as "GASTOV" from Kenya Industrial Research and Development Institute (KIRDI). It uses small pieces of firewood measuring about 20cm in length and 5cm in diameter and crop residues. The gasifier is ignited at the top and the primary air enters at the bottom and moves up through the packed bed of fuel. Secondary air enters from below into the top section, where it mixes with the gases for combustion. The details about the dimensions and different parts of the gasifier stove can be found in Gitau et al. [36].

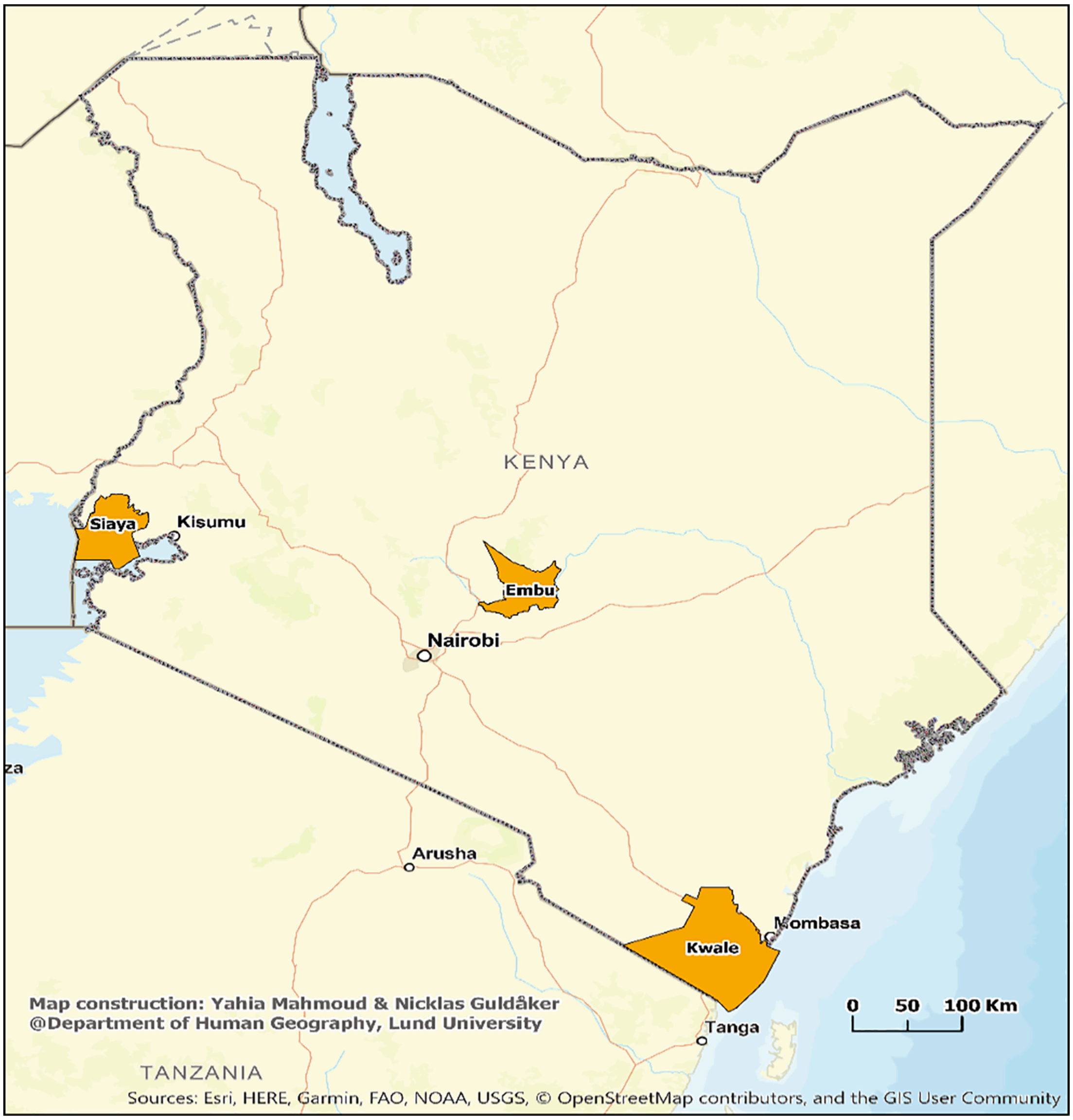

Fig. 1. Map of Kenya with Siaya, Embu and Kwale counties highlighted in orange.

following preliminary results from our experimental and participatory studies [13,14,36–38]. Secondly, at gathering data, based on farmers' observations and perceptions on the feasibility, preliminary impacts and acceptance of the technology. Among the variables gathered here, we find the *use of stoves*, *most used feedstock* as well as *use of the produced biochar*.

The feedback gathered by researchers and field assistants served as the basis for discussions in the workshops. In these, farmers worked in focus groups and in general assemblies. Besides, semi-structured interviews were conducted with 20 households on each site. The latter were selected based on the principle of availability and then on a random selection of those available. Our field assistants were instructed to contact all households participating in the project and inform about the workshops. They also asked about the availability of households for individual interviews outside the frame of the workshop. From this shortened list, the ones to be interviewed were selected randomly.

For pedagogic reasons, the topics discussed during the workshops were organized following three stages of biochar-production and use, namely pre-cooking, cooking and post-cooking phases (see Table 1). In relation to the pre-cooking phase, we asked questions related to the feedstock (gathering, preparation, storage, use, preferences, economic perceptions, etc.). As for the cooking phase, we asked about the positive/negative aspects of using the stoves, use frequency, kinds of foods cooked/excluded and why, perceptions on energy savings, and so on. Lastly, we evaluated the aspects that happen during the post-cooking phase such as the collection of the char, its application to the soil and beyond (handling of the biochar, its application, impacts on the yield, economic evaluation, etc.).

Based on data captured during these workshops we carried out semi-structured qualitative interviews with 60 households, addressing: (a) the degree of feasibility, (b) the immediate perceived results, (c) the general attitudes towards the idea of using the cooking stoves to produce biochar, and (d) patterns of feedstock use. These results are presented in Section 4.2.

3.3. Limitations

The approach used here has both strengths and limitations. Among the strengths, we find the participatory character that goes beyond knowledge construction based solely on the experts' controlled experiments. The stakeholder's observation and experiences are crucial to predict if the attempted strategy is taking hold or not. However,

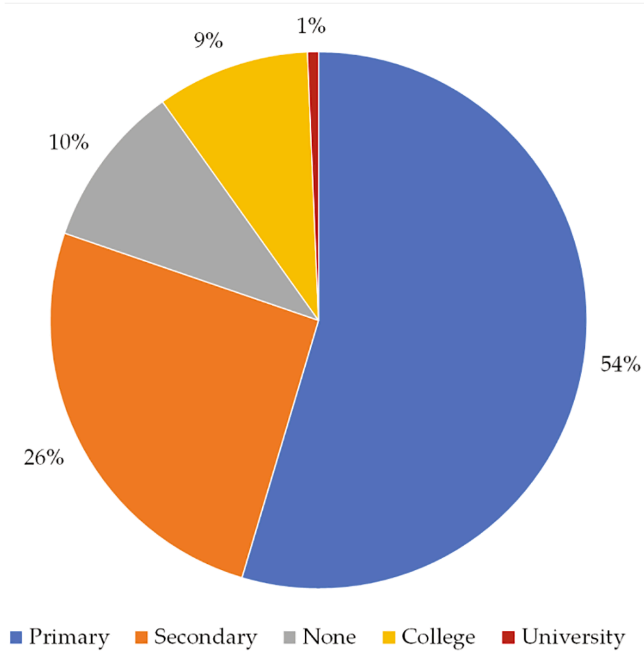

Fig. 2. Educational level of household-heads (in%) for all study areas.

Table 1
Workshop structure.

	Pre-cooking	Cooking	Post-cooking
Topics	Evaluation of what happens before cooking.	Reflections, problems, suggestions on the process during cooking.	Discussions of what happens after cooking.
Examples	Feedstock collection, preparation, storage, use, preferences, economic consequences, etc.	Feeding the gasifier, lighting up, use frequency, foods cooked/excluded, perceptions on energy savings, etc.	Biochar harvest, storage, application, yield impacts, economic evaluation, etc.

studying human perceptions is always a complicated matter. For instance, when different farmers mention yield or economic improvements these might entail different things. Furthermore, the follow-up studies did not allow for a full random selection. Lastly, evaluating changes after only two years has both positive and negative implications. On the one hand, it gave the possibility to adjust things and assist end-users. On the other hand, two-years is a short period to evaluate if a transition is taking place.

4. Results

4.1. The baseline study

We provide an overview of the socio-economic conditions at the onset of the project to evaluate the need for experimenting with biochar, the communities' willingness to adopt it and the benefits it might bring. After that, we present the patterns of fertilizer use, cooking fuel energy uses and the availability of suitable feedstock for biochar production.

4.1.1. Socio-economic conditions

This mapping aims to create a basis for future exploration of the correlations between the variables captured here (i.e. age/gender of household heads, educational level, family demographics, livelihoods, resources owned and farm size) and the levels and ways of adoption.

In Siaya 31% of households surveyed were female-headed, in Embu 21% and in Kwale only 17.5%. Ages ranged between 23 and 87 years. In Embu, 47% of household-heads had completed primary school, 31% secondary school and 16% college. Compared to the other areas, surveyed household-heads in Embu portrayed higher levels of formal education.

In Siaya, 61% had completed primary school, 18% secondary school and 7% college. In Kwale, household-heads with no formal education was the highest (9 cases), but 45% had attended primary school and 27.5% secondary school.

Secondary school attendance was higher among males, a group traditionally favoured to pursue formal education, while the highest female drop out happens during secondary school as girls are forced to engage in household activities.

Independent of educational level, labour division inside household was traditional. Cooking and doing laundry was, in over 90% of cases, done by female adults with some help from young girls and, to a lesser extent, boys. Although shared in many cases, farming was a male responsibility. With degree of variation, transporting and selling goods was a shared responsibility.

Household demographics were similar in all counties. The most visible deviation was the low percentage of families in Embu with children younger than six years. Although the average number of household members is similar in all sites, variation among households was wide. We found households with as few as one member and as many as 19.

In matters of livelihoods, the figures were very similar amongst sites with the exception of the low percentage of people engaged in economic activities outside family farms in Siaya. Likewise, livestock ownership was disparate with households having up to ten animals[2] and those owning none. Most households rearing animals did it exclusively to cover family needs. Four cases in Siaya owned between 40 and 50 chickens for commercial purposes and one in Kwale had a bigger poultry farm.

This variation of cases creates good premises for studying linkages between the socio-economic characteristics of the household and the adoption of biochar. Table 2 summarizes the picture.

Table 2
Household demographics, livelihood strategies and assets.

	Embu	Siaya	Kwale
Households			
With children 0–5 years	19%	53%	45%
With children 6–18 living permanently in	66%	80%	75%
Less than 3 permanent members 19–55	61%	78%	67.5%
Average of permanent members	4	6	6
Livelihood Strategies			
Household-heads with farming as main occupation	97%	95%	83%
Members working outside family-farm, but supporting the household	28%	14.5%	27.5%
Households receiving support from family members not part of household	30%	31%	25%
*Household Assets**			
Average farm size	2.4 acres	2.3 acres	3 acres
Owning land individually	100%	100%	90%
Owning cows	79%	62%	62.5%
Owning goats or sheep	49%	51%	35%
Owning oxen	16%	51%	32.5%

* Almost all kept poultry and to some extent rabbits.

[2] This does not include poultry or rabbits.

4.1.2. Fertilizer uses

Research shows that biochar can, depending on combination with fertilizers, impact crop yields between −29 and +324% [38,45–47].

Excluding two, all households surveyed in Embu used inorganic fertilizers due to the widespread production of cash crops such as coffee and tea. The average expenditure on fertilizers was 15,000 Kenyan Shillings (KES) per year.[3] Most households (72%) used ashes from cooking as soil amendment and organic fertilizers.[4] All were willing to experiment with alternatives to improve yields (57%) and reduce costs (28%).

In Siaya, 78% of households used inorganic fertilizers and spent an average of 6800 KES per year. Using ashes and manure was a common practice (69%). As in Embu, the interest in alternatives to improve soil-health was high (82%).

Kwale had the lowest use of inorganic fertilizers, something likely associated to declining crop productivity caused by prolonged dry periods [48]. Only five households used them and spent an average of 1520 KES per year. All households used organic fertilizers and a majority applied ashes (Fig. 3). Most households had also access to manure on farm. Similar to previous sites, households in Kwale were willing to experiment with new alternatives to improve yields (79%) and reduce costs (10%).

4.1.3. Cooking fuel and energy uses

Surveyed households used firewood as fuel energy and most had trees on farm. This was the case of 74% in Embu, 63% in Siaya and 75% in Kwale. Another study in Embu shows that trees on farm stand for 65% of the firewood [13]. Time spent on firewood collection depended on the proximity to collection sites and the amounts consumed. The average was 31 h per month in Embu, 28 h/m in Siaya and 17 h/m in Kwale. Some collected once weekly or monthly, while others did it on daily basis. Few households spent up to 1500 KES per month to purchase firewood. The second most used fuel is charcoal, consumed by 89% of households in Siaya, 72% in Embu and 35% in Kwale. Of them, 27% bought firewood and 61% charcoal on regular basis (see Fig. 4).

Although some households used up to three types of stoves indoors, most used only one. The predominant was the three stone stove[5] with firewood as feedstock, followed by improved jikos[6] with charcoal, firewood or organic residues, and standard jikos with charcoal. Gas-cookers, kerosene stoves and electric kettles were rare (see Fig. 5). Many households (72%) did not use stoves outdoors, while 25% used occasionally the three stones.

Besides cooking, fire is used to heat water, warm rooms and iron clothes using charcoal iron boxes. Most respondents (69%) experienced direct contact with smoke as a health hazard causing sneezing, running noses, eye problems and coughing. All declared interest in cleaner technologies and fuels.

4.1.4. Potential feedstocks for biochar production

The availability of residues suitable for biochar production and their present uses were mapped. This was done in order to meet the observation that biochar-production consumes organic materials that normally end up in and are beneficial for soils [49].

Nearly all households (96%) had maize stovers and cobs. In 34% of cases, stovers were used as fodder. In Embu and Siaya they were also used as fuel or to light fires, but rarely so in Kwale. Likewise, 75% of households used maize cobs as fuel or for lighting fire, and to a lesser degree as animal fodder (6.5%). Of 150 households, 5.3% used cobs as fertilizer and an equivalent percentage (5.3%) did not use them at all. This makes maize cobs a good candidate for biochar production, particularly in Siaya and Kwale as they are already used for energy purposes.

Most households (87%) had dry manure but in most cases (84%) it was used as fertilizer. Other feedstock are tree prunings, dried mango stones, banana leaves and dry leaves. Most households have access to prunings on farm and they were used as firewood, animal beddings, mulching or for construction. In contrast, few used dried mango stones for specific purposes. Only 15,3% of households used them as seedling and another 7.3% as manure. Banana leaves were available to 85% of households and used them as animal fodder, for wrapping, packaging or cooking. Dry tree leaves were used for mulching, producing manure, lighting up the fire, or as animal beddings. Two other residues with good potentials for biochar production are coffee husk, widely available in Embu, and coconut shells and trunks available in Kwale.

Despite varied demographic and socioeconomic conditions, both inside and among sites, there were patterns of commonality. First, all households faced fuel shortages and used inefficient technologies. Second, all sites experienced problems related to soil degradation. Third, the technologies used burdened mostly females. Fourth, all households were interested in alternatives that could tackle these problems. Based on this, it can be concluded that there was a need for and a willingness to experiment with the production and use of biochar.

4.2. The Follow-up studies

Two years after the introduction of the gasifiers, we organized workshops that followed a semi-open structure including all households. These started with focus groups that lasted between 4 and 6 h and mapped experiences, results and difficulties faced. After that, the groups presented to each other and discussed their findings. To dive into some of the topics brought up by the workshops, we interviewed 20 households per site. The following section present the main topics.

4.2.1. Degree of feasibility of on-farm biochar production

Harvesting the char was the easiest for 62% of the interviewees, while chopping the feedstock into suitable sizes was the most difficult (75%). Likewise, 30% of respondents mentioned refilling the canister as a difficult step[7] affecting the whole cooking, as some foods do not allow for interruption in the middle of the cooking process without being spoiled.

In relation to biochar application, placing it into furrows was not a problem for the majority (67%). However, measuring plots correctly (45%) and making furrows (33%) were experienced as cumbersome. Another 25% saw distributing biochar equally into the furrows as challenging.

To conclude the inquiry on the degree of feasibility we asked the following questions: (1) Do you find biochar production time consuming?, (2) Do you find collecting, drying, and storing organic residues for biochar production time consuming?, (3) Do you find it meaningful to produce biochar at home? and Why?

In relation to question (1) half of respondents (31 in total) did not find this task time consuming, while 29 thought otherwise. When we refined the question by asking about the collection, drying and storing of the feedstock (question 2) 35 of 60 saw this part of the process as time consuming. Nevertheless, when asked about continuing with biochar (question 3) all respondents confirmed their continuation. The reasons given were: (a) *mainly because of the impacts on crop yields* (25%), (b) *mainly because of the energy benefits* (7%), and 68% stated the reason to be both (c) *the energy benefits as well as the impacts on the soil.*

[3] Around 136 US dollars.

[4] Mainly manure.

[5] Three stones of the same height on which a cooking utensile can be balanced over a fire.

[6] Jikos are portable stoves used for cooking.

[7] Gasifiers came with one canister, but when refilling was reported as difficult an additional canister was delivered.

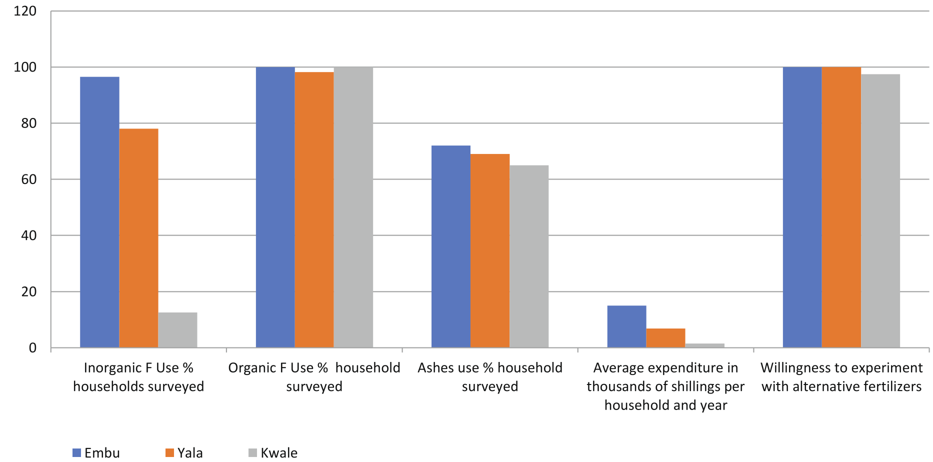

Fig. 3. Use of fertilizers, expenditure and willingness to experiment with new alternative.

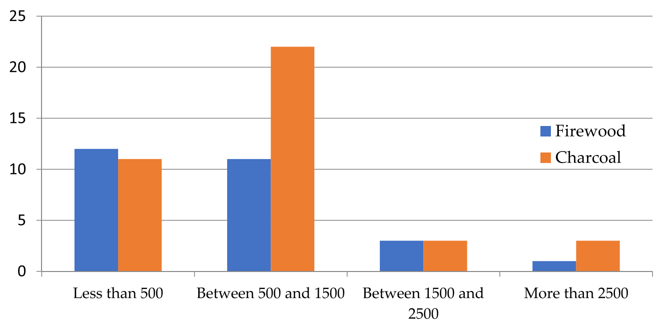

Fig. 4. Amount of KES spent monthly on fuel sources.

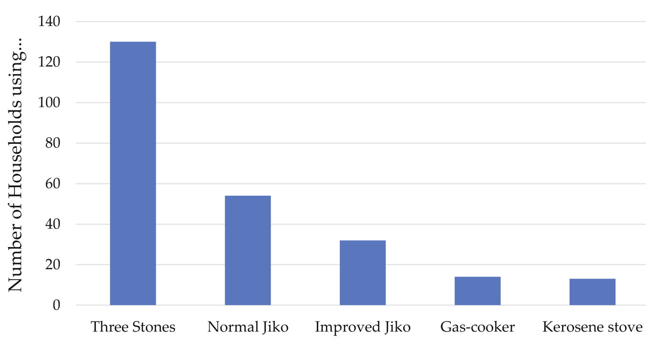

Fig. 5. Type of stoves used indoors.

4.2.2. Immediate perceived results

The perceived results were clustered in several themes: preliminary perceptions on the use of biochar as a source of energy, as a soil amendment, comparative advantages of using the cookstove and finally the participant's perception of health and economic impacts.

When asked if they experienced any benefits in using biochar for energy purposes, 77% of respondents answered positively. Of those, 33% stated that it saves money, another 33% that it was a good cooking alternative and 12% that it produces less smoke compared to other alternatives. So far, 63% of respondents did not experience negative aspects worthwhile reporting. However, some referred to the already mentioned challenging parts, such as chopping the feedstock into the required size, refilling the canister and lighting from the top.

More notable, 96% of respondents stated to have observed positive impacts on soil health. Of them, 95% mentioned improvement of soil fertility, 25% observe moisture retention in the soil and 12% believe there is less crop pest attacks.

Besides the challenges already mentioned, 53% of respondents found the cooking stoves easy to use although more suitable for foods requiring short time to cook. All respondents found them to be a cleaner alternative producing less smoke, less soot and fewer ashes. Some found them even to be less harmful to cooking utensils and others stated that food tasted less smoke.

As during the baseline study 69% of respondents mentioned the incidence of sneezing, running noses, eye problems and coughing caused by the smoke, we asked about their experiences with the gasifier cooking stoves. All respondents claimed them to be a better option as they produce less smoke and minimize direct exposure to flames. A parallel study that compared gasifiers to the three-stones shows a reduction in concentrations of carbon monoxide and fine particulate matter by 40–97% [14,36].

Simultaneously, households interviewed during the follow-up studies experienced improvement in overall economy, due mostly to reduction of fuel expenses. A whole 98% asserts to use less feedstock thanks to the cooking stoves and 95% experiences crop yield improvements, not only in quantitative terms but also in qualitative ones. The third most given example was the reduction of expenses in fertilizers. Because of this, they feel a reduction in expenses and an improvement in incomes. We sum up in Table 3 these perceived benefits.

4.2.3. Attitudes towards on-farm biochar production

To have a sense of the way the communities were relating to this strategy, we discussed a set of questions related to degree of acceptance. We asked about intentions to carry on using the cooking stoves and producing biochar, the kinds of foods cooked on the stoves, the reactions of family members and neighbors towards the cooking stoves, as well as the willingness of households to buy the stoves.

All households intended to continue producing biochar for energy and soil amendment purposes. The main reasons given are to reduce energy costs and improve crop yields. The vast majority (87%) is intending to use the biochar produced as soil amendment, while only 13% preferred the option of re-using it as energy.

Most informants agreed that stoves were more suitable for foods that cook fast and do not require refilling the canister. We also inquired about the attitudes of family members towards them and 53 out of 60 stated it to be positive. Some of the aspects that household members appreciated in the cooking stoves were: they produce less smoke (30%), they cook faster (23%), they use less fuel (14%) and once started they do not require much attendance (12%). The few negative reactions reported by the interviewees were the degree of difficulty to light up the stoves (8%) and the tiresome character of chopping the feedstock into the required size (6%).

Table 3
Immediate perceived results from producing and using biochar.

Benefits in energy terms			Benefits in terms of soil management		
77% of respondents claim to experience benefits			96% of respondents claim to experience benefits		
33% it saves money	33% it is a good cooking alternative	12% it produces less smoke than traditional alternatives	95% it improves soil fertility	25% it retains moisture	12% there is less pest attacks
98% asserts to use less feedstock			95% experienced *crop yield improvements* both in quantitative and qualitative terms		

In all sites, neighbors were curious about the stoves and the way they operate. Some of them were also interested in obtaining one. These quotes capture this: "…they are very interested to know how it works (…) where they can get one and at how much. They mainly like it because it uses less fuel, smokes less and it is portable", or "…they like and want to learn how the stove works and where they can buy one".

As in the initial stage of the project households were told the gasifiers will only be available during the duration of the studies, we asked now if they would want to buy them at a 'reasonable price'. Without inquiring too much into what a 'reasonable price' meant, 98% of households stated willingness to pay for them. Furthermore, several non-participant households were interested in buying them. As many respondents mentioned *chopping the feedstock into the right size* as a difficult task, we inquired about the willingness to pay for a ready-to-go feedstock and 48% were willing to do so.

4.2.4. Patterns of feedstock use

As trees and tree prunings dominate the feedstock used for cooking, 20 households per site were asked about the most used trees. In Embu, respondents mentioned 12 different species. Topping the list were Grevillea, used by all these households, coffee prunings used by 85% and macadamia pruning used by 65%. In Siaya, households used 17 different species and the commonest were Makhemia (95%), Guava (70%) and Eucalyptus (45%). While in Kwale, respondents mentioned 23 species dominated by Mango (55%), Muarubaini (50%) and Neem (45%). Interviewees were also asked about their favorite feedstock. In Embu, it was coffee prunings and the reasons given by them for this is that it gives a good char (95%), it burns long (70%) and it gives a good flame (55%). In the case of Siaya, the favorite one was Makhemia and the reasons given were it burns long (65%), it gives a good flame (45%) and it gives good char (45%). Respondents in Kwale mentioned Neem as the favorite feedstock as it gives good char (95%), it burns long (70%) and it gives a good flame (55%). According to these respondents, the most important characteristic for the feedstock is that it should: give good char (70%), burn long (63.3%) and give a good flame (48.3%).

As these stoves can use various organic residues, we inquired if new residues were incorporated as feedstock for energy purposes. In Siaya, out of 20 respondents 17 were not using any new feedstock, in Embu that number was 14, while in Kwale only 8 did not, opening up for the possibility that in Kwale the variation of feedstock used might have increased. However, wood, mostly from tree prunings, still dominates the feedstock used for energy purposes (see Table 4).

Table 4
Feedstock uses and preferences.

	Most used tree species for energy production (mostly in the form of prunings)		
Location	Embu	Siaya	Kwale
Number of different species	12	17	23
Top 3 species used	1. Grevillea 2. Coffee 3. 3. Macadamia	1. Makhemia 2. Guava 3. 3. Eucalyptus	1. Neem 2. Mango 3. 3. Coconut
Top characteristics for feedstock choice:	1. It should give good char (70%) 2. It should burn long (63.3%) and 3. 3. It should have a good flame (48.3%).		

5. Discussion

Innovation is seldom a neutral introduction of new technologies or ways of doing things. It is the complex process involved in uncovering and materializing those ways. Innovations have been critical for the survival and success of social organizations. More often than not, the processes shaping innovation can favor, intentionally or unintentionally, some social groups, organizations or life styles over others. Hence, innovations cannot be divorced from the historical and political context in which they evolve.

The drastic impacts of climate change in sub-Saharan Africa has led to the introduction of and experimentation with an array of ́climate-friendlý innovations that promise improving the lives of rural communities while decreasing their ecological footprint. The entry points are many and mapping them is beyond the aims of this article. However, the most common ones focus on new ways to manage efficiently limited natural resources such as land, water or forests. These resources are still key for the production and reproduction of the material life in rural Africa, where we also see increasing demand for traditional fuels and a decline in soil fertility.

In sub-Saharan Africa, wood fuel still accounts for 60–95 per cent of total national energy use [50]. Likewise, research on soil fertility, crop nutrition and socioeconomics in African agro-ecosystems has shown the need for investments in organic inputs, inorganic fertilizers, and improved agronomic management as a way to achieve sustainable increases in crop productivity [38,51]. Moreover, the dominant cooking techniques in rural Africa have been associated with negative health impacts, particularly on women and children. These three ailments, namely energy 'poverty', food insecurity and excess exposure to smoke during cooking are three sides of the phenomenon that this research project had set to understand and tackle.

Based on the above, this study explored the socio-cultural and agro-ecological conditions in three diverse areas in order to assess the need for and feasibility of introducing a sustainable management strategy that tackles energy efficiency as well as soil and human health. As our baseline study showed the weight of expenditure on fuel and fertilizers, our objective was to test empirically the impact of biochar production on energy efficiency and soil fertility. All households approached were willing to produce, use and experiment with biochar. The driving motives were to improve yields, reduce costs of various kinds and minimize exposure to smoke.

Starting with an approach that uses smallholder-farming systems as its scale of analysis and experimentation, we studied (1) the feasibility of on-farm biochar production, (2) the impacts of this practice on fuel-use efficiency and on soil fertility [37] and (3) the general outcomes for the economy and health as perceived by participating households.

Selected households were provided with gasifiers and trained on their use. The process of production and consumption of biochar relied completely on the household own resources. After two years of production and application of biochar, half of respondents stated to find the production of biochar time consuming due to the process of collection, drying, storing and, above all, cutting the feedstock in suitable sizes. Notwithstanding, all of them were planning to continue producing biochar as they perceived positive impacts on energy efficiency, soil productivity, reduction of smoke exposure and improvement of household economy.

Despite these positive attitudes, our observations reveal a variation, among sites and households, in levels of adoption. This variation seems to be complex and not necessarily static. The labour-demanding tasks involved in fuel preparation vary from household to household depending on demographics, accessibility to fuel sources and stoves available in the household. Likewise, the dietary habits and kinds of meals cooked have consequences on the frequency of use of cooking stoves. In our concluding remarks, we take up some of the observations that shed light on the nature of this variation.

6. Concluding remarks

These conclusions stem mainly from the studies on participants' observations and perceptions. As such, they should be taken as a partial representation. Some of them are in line with our experimental studies and preliminary results [13,14,36–38], others less. However, these perceptions are useful for designing more focused studies that could help understand and tackle the issues and topics brought forward by this study. The need for understanding these complexities is also confirmed by other studies [31,35].

The conditions that will enable or hinder a successful adoption of biochar go from material ones, such as the characteristics of local environments and the socio-economic conditions of households, to psycho-culture ones, such as habits and preferences.

To start with, 95% of respondents that participated in the follow-up studies perceive *crop yield improvements,* not only in quantitative terms but also in qualitative ones, and 77% state to experience positive impacts on *energy efficiency*. Although the vast majority claims that it will continue producing biochar, we believe this will depend on contextual aspects.

First, we could observe that in those places with no access to forest, people are more eager to reduce fuel consumption and costs (e.g. Siaya). This stands in contrast to places where access to firewood from both pruning trees on farm and forest has guaranteed fuel throughout the years (e.g. Embu).

Second, the cooking stoves experimented with require dry and size-specific feedstock. In Embu, many respondents gave the "lack of access" to dry feedstock as the reason to use flexible options such as the three-stone. Cutting wood into the right size seems also to be challenging for many. It is easier to cut firewood into small pieces when wet and allow the wood to dry well for later use during the rainy season, as observed by other studies [13]. As this population have access to firewood on farm and from forests, this affects their planning cycle. Drying has a longer planning cycle than cutting, but both affect the patterns of cookstove use. Households that dry wood on a seasonal cycle are more likely to use it for both energy and agronomic purposes. We observed a variation in this planning cycle that go from daily to monthly ones. The shorter this cycle the higher the risk of using the pyrolytic cookstove on a seasonal basis. Households in this category use the cooking stoves for biochar production and not as a means to reduce energy expenses. This might be explained by the fact that biochar is mostly associated with its agronomic benefits.

Third, the adoption of pyrolytic gasifiers will also depend on the alternatives available. The three-stone stove is the most established one and its advantages as expressed by users are:

1. Feedstock related: it can use any kind of feedstock, with any size and, practically, with any level of moisture.
2. Size and heat: most respondents praise the three-stone for its versatility. The size of the three-stone cookstove allow for change at any time to suit different purposes. Likewise, its heat can 'easily' be controlled.
3. Monetary costs: perhaps one of the most important advantages of three-stone is the fact that does not require any investment.

Fourth, the strategy proposed by this project risks to be used to its half-potential as some households used the gasifiers either for agronomic or energy purposes, and not for both.

Fifth, although a whole 98% of respondents asserts to use less feedstock since the introduction of the gasifiers, in all sites wood is still the dominating fuel type used for cooking. This is also something that deviates from our initial hopes, as the cooking stoves are designed to use a variety of organic residues.

All in all, this initial data and observations show that if introduced correctly, this technology might represent a viable strategy to help these communities tackle issues of *soil fertility*, *fuel efficiency* and exposure to *indoor smoke*. Besides positive impacts on household economies and their environments, this technology simplifies activities carried out mostly by female labour.

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CRediT authorship contribution statement

Yahia Mahmoud: Conceptualization, Methodology, Investigation, Data curation, Validation, Writing - original draft, Writing - review & editing. **Mary Njenga:** Methodology, Investigation, Validation, Writing - review & editing. **Cecilia Sundberg:** Methodology, Validation, Writing - review & editing, Project administration. **Kristina Roing Nowina:** Methodology, Investigation, Validation, Writing - review & editing, Project administration.

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.

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