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Determinants and success of engagement in circular bioeconomy practices in African food systems

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ABSTRACT

Ending hunger and ensuring sustainable food production and consumption patterns globally, as outlined in the United Nations 2030 agenda of sustainable development goals (SDGs), cannot be accomplished through a linear resource use model that has proven to be non-restorative and unsustainable. Therefore, a more sustainable model of resource use - the circular bioeconomy (CB) - has been proposed as an alternative to achieve circular, resilient, and sustainable food systems. This approach can help achieve strategic SDGs reliably. However, there is currently insufficient evidence regarding the factors that contribute successfully to the likelihood of engagement in CB practices, particularly in smallholder households in vulnerable global regions such as Africa. To address the breach, this study evaluated three pairs of CB practices, and multivariate probit regressions were applied to identify the factors that influence smallholders' engagement in CB practices. The study aimed to predict the probabilities of engagement among smallholders in the Democratic Republic of the Congo (DRC), Ethiopia, Rwanda, and South Africa. The results showed that sorting organic from inorganic waste and using organic waste as compost had a 31 % likelihood of contributing to successful engagement in CB practices while sorting waste and using organic waste as livestock feed contributed to such success by 17 %. Using organic waste as compost and livestock, feed had the lowest success rate of 11 %. Thus, CB innovations that promote combinations of CB practices among smallholders, particularly those that involve sorting waste and using organic waste as compost, have a higher chance of succeeding in achieving circular food systems.

1. Introduction

Valorisation and development of biological waste ending hunger, and ensuring sustainable production and consumption patterns globally are some of the key Sustainable Development Goals (SDGs) of strategic importance in the United Nation's 2030 agenda (UN, 2015). The circular bioeconomy can serve as a bridge to both urban and farming communities. The World Global Bioeconomy Summit (GBS) (GBS, 2018) identifies bioeconomy in the sense of safeguarding biological resources, their production and utilization, encompassing therein science, innovation, technology, and associated knowledge to provide missions in economic sectors, products, processes and information to achieve the goal of a sustainable economy. However, achieving such SDGs that are essential for human survival is in jeopardy, because of the heavy reliance on global production (Geissdoerfer et al., 2017) and consumption systems, on a non restorative and wasteful resource use model (Korhonen et al., 2017; 2018), the linear model, which has been found unsustainable by researchers (Kirchherr et al. 2018; Feleke et al. 2021). The linear model focuses on extracting resources from nature, to produce consumables, and then dispose of waste after consumption (EMF, 2019). Consequently, the linear model leads to excessive use of resources per unit of production, and waste of resources in disposing of waste that

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accumulates into environmental nuisances across many urban and rural centres, if not recycled and reused in production (Dasgupta, 2021). Hence, for some authors (GGGI, 2020; Krütli et al. 2018; Kaza et al. 2018) maintaining nutrient loops within production and consumption renders food systems non-resilient, and unsustainable. Non-resilient and unsustainable food systems cannot be reliable and effective towards achieving key SDGs of the 2030 agenda (Tanumihardjo et al., 2020). To curb the damage and risk posed by the linearity of resource use in food systems, a complementary and sustainable model of resource use – the circular bioeconomy model – has been proposed.

A circular bioeconomy (CB) model as defined in literature by researchers (Jurgilevich et al. 2016; El-Chichakli, et al. 2016; Corrado & Sala, 2018; Carus & Dammer, 2018; Issa et al. 2019; Feleke et al. 2021; Sekabira et al. 2021) as uses biological mechanisms to reduce wastage during production, recycle, and reuse waste in agricultural production. Therefore, scholars (Issa et al. 2019; Tanumihardjo et al. 2020; Feleke et al. 2021) attested that, the CB model closes nutrient loops in food systems, thereby making them resilient and sustainable. Unfortunately, despite its hypothesized centrality towards sustainable resources use and thus sustainable food systems. There has yet been minimal scientific efforts in circular bio economy researchs (Geissdoerfer et al., 2023; Tanumihardjo et al. 2020; Feleke et al. 2021) dedicated to studying mechanisms of how the circular model should be established at scale and effectively, within global food systems more so those of the most vulnerable regions like Africa. At least, available efforts have been motivated by business entities interested in financial returns than improvement of the UN's SDGs 2030 agenda, which get focus on vulnerable populations (Geissdoerfer et al., 2023; Tanumihardjo et al., 2020; Feleke et al., 2021). However, with a number of circular initiatives increasingly popping-up in Africa, scientifics (Krütli et al. 2018 and Madau et al. 2020) interest is growing to provide communities, private investors, and governments with empirical evidence on designing and developing cost-effective and socially acceptable CB innovations, and how these can be scaled to establish the intended circular food systems. There is another knowledge gap in Africa on how communities must be effectively guided on several dimensions of CB innovations from designing to implementation.

According to Holt-Giménez & Shattuck (2011) African food systems are dominated by smallholder farmers in production, and low-income earners as consumers. In the continent, agriculture is dominantly dependent on natural provisions such as rains and weather, oceans, land and gassers with minimal inputs (fertilizers, irrigation, mechanization etc.) making the region's food systems very vulnerable (pests and diseases, droughts, storms etc.). Scholars (Marenya & Barrett,2007; Teklewold et al. 2013; Kassie et al. 2015; Makate et al. 2019) attested that, farmers consequently, by default adopt several agricultural practices concurrently to minimize risks. Yet, gap still on in research, to understanding the importance of what influences smallholders' success with engagement on CB practices in African food systems. Thus, authors (Marenya & Barrett, 2007; Kassie et al. 2015; Makate et al. 2019) elucidated in literature the need of an approach that assesses the likelihood that engagement on CB practices outcome successfully. This compatibility could be more informative if it also explores possible combinations because the adoption of multiple agricultural practices is often associated to greater multiple benefits such as higher farm productivity and better income by smallholders.

Consequently, this paper intends to fill the gap in the literature by evaluating three pairs of CB practices, and applied multivariate probit regressions to identify the factors that influence smallholders' engagement in CB practices. The study aimed to predict the probabilities of engagement among smallholders in the Democratic Republic of the Congo (DRC), Ethiopia, Rwanda, and South Africa. CB practises are explored in pairs, and the anticipated success probabilities for each pair are generated in the context of smallholder actors in critical food commodity value chains. Specifically, the paper explores determinants of combinations of CB practices among smallholders and it predicts how successfully these combinations could be adopted. As a result, this study helps to highlight which socioeconomic factors successfully contributed to the likelihood of engagement in circular bioeconomy practices. Particularly in the context of smallholder households in the most vulnerable global regions such as Africa, which CB practice, combinations could currently prevail across African smallholder food systems, with what probability, and what determines this success. Therefore, this study's findings are invaluable in identifying priority areas for policy implementation regarding CB practices, which can pave the way for the establishment of extensive circular food systems in Africa. Accordingly, the study is structured as follows: firstly, the conceptual framework, materials, and methodologies are introduced; secondly, the outcomes are delineated. Lastly, the third section comprises a concurrent discussion, followed by an exploration of the study's limitations and strengths, and ultimately, policy recommendations are presented in the conclusion.

2. Conceptual framework

The term circular bioeconomy refers to the valorisation and development of biological waste (Negi et al., 2021). In Fig. 1, we present our conceptual framework where we hypothesize differential influences of contextual and household characteristics on CB practices or their combinations, which in the end influences attainment of circular food systems. We hypothesize that different factors can enable or hinder engagement into CB practices or their combinations at household level as stated by Sally Bryant (2017). Later, we shall go over the hypothesised influence directions. For this study, we are curious about how these characteristics can encourage households to engage in a variety of CB practise combinations, which we have highlighted in orange in our framework. As a result, we study the nature of direct relationships between these elements and CB practise combinations, which are highlighted in continuous lines on the framework. However, we admit that there are other correlations between these characteristics and engagement in individual CB practises, which we depict with dotted lines but do not examine separately. Our interest in combinations is informed from literature and field experiences that smallholder households usually engage in more than one practices, or innovations, or practices, or technologies around a common agricultural aspect (Marenya & Barrett, 2007; Teklewold et al. 2013; Kassie et al. 2015). We also acknowledge that there are direct associations between CB practices, their combinations and attainment of circular food systems, but we also do not analyse these in this paper.

3. Materials and methods

3.1. Sampling procedure and data

Data was initially collected in city-regions of four African countries, as illustrated in Fig. 2. The data was collected based on four strategic food commodity value chains: coffee in DRC, bananas in Ethiopia, cassava in Rwanda, and vegetables in South Africa. The aim of this innovative and trans-disciplinary approach was to valorise rural and urban organic waste into reusable products in agricultural production, such as compost and livestock feed, in order to create more resilient food systems (Sekabira et al., 2021, 2022 ; RUNRES 2023). The household sampling process involved a two-stage procedure. Firstly, local organizations that practice CB were chosen based on their proposals for cost-effective and socially acceptable CB innovations. The selected innovations across all countries included valorisation of organic waste, household waste, green waste, and human waste into compost, biochar, struvite, and livestock feeds. Additionally, small-scale innovations that processed bananas into flour were also selected. Three organizations were selected from DRC, four from Ethiopia, three from Rwanda, and three from South Africa. The numbers of organizations selected varied from country to country because after reviewing all the competing organizations in each country, different numbers of successful organizations were chosen. Organizations were asked to present lists of their members, who would presumably benefit from their CB innovations at a later stage. Then, from these membership lists, fifty (50) households were selected randomly from each local organization to qualify for data collection interviews. Subsequently, the random selection of participants from available lists generated a population sample of 256 households from DRC, 139 from Ethiopia, 187 from Rwanda, and 195 from South Africa, thus a total of sample size of 777 households (Fig. 2).

During the interviews, we asked both closed and open-ended questions about various household demographics such as location, size, education, income, and its sources, as well as the age and gender of household heads. We also inquired about the current CB practices of the households and their access to resources, including mobile phones, credit, markets, land, and technical equipment. The data was collected electronically using open data kit (ODK) computer packages between August and December 2019. Trained enumerators, who were graduates from local universities in fields related to agricultural sciences, assisted with the data collection. These enumerators were able to speak both the local language and English, which allowed for enumeration in local languages while data inputs were in English. It is important to note that the data analyzed here were collected before RUNRES began implementing CB innovations, to fully comprehend the CB status quo. The locations within these countries were referred to as RUNRES city-regions, which were purposely selected due to their dominant production of the food commodities of interest, as well as their existing connections with project partners and stakeholders. These city-regions and their respective food commodities were Kamonyi of Rwanda for bananas, Bukavu of DRC for coffee, Arba Minch of Ethiopia for vegetables, and Msunduzi in South Africa for cassava.

After selecting the city-regions, we proceeded to identify the most relevant food commodities in each area. We did this by conducting preliminary and participatory work with our stakeholder networks. This work was participatory in nature, meaning that all RUNRES stakeholders from the private, academic, public sector, funders, and local communities willing to participate were involved in designing the RUNRES approach, food commodity value chains, and fitting innovations. Transdisciplinary workshops were organized by the RUNRES team to facilitate this process. The main project private sector partners in all countries were garbage collection companies, while main public partners were municipal authorities. Within each city region, we selected various administrative sub-divisions randomly (we listed all sub-divisions from each city-region, and randomly selected those we worked with). To select respondent households, we used a systematic random sampling method from the available household lists in each respective sub-division. In Rwanda, we obtained household lists from sector (subdivision) offices for farmers and consumers. We surveyed every fifth interval household in Rwanda, every sixth interval household in Ethiopia, and every seventh interval household in DRC and South Africa. These intervals were used to avoid a sample dominated by certain villages/cells (smallest administrative unit) within the city-region–thus the selections were differently probabilistic. In Ethiopia, household lists were obtained from *Kabele* (sub-division) offices for farmers and South Africa from Msunduzi municipality and organization involving into Cassava production. While in DRC, a farmers' list was obtained from the national coffee office in Bukavu and validated by coffee cooperatives. The reason for this was that there were only a few of these actors and they were sparsely distributed. Our study obtained ethics approval from RUNRES and adhered to the ethics clearance of the Ethics Commission of ETH, Zurich, under the reference number EK 2020-N-51 (approved in June 2020).

ETH Zurich is the overall implementing institution for the RUNRES project. The survey protocol was tested on a trial sample in the target city-regions to validate that respondent could understand the questions as intended, and after identification of the respondents, we then administered the survey to final respondents. Each respondent would have an independent section within a common survey tool with closed and open-ended questions. Our study focused on interviewing the heads of households who were primarily responsible for making important decisions for the household. In cases where the heads of households were not available, we interviewed their spouses who usually had a secondary role in decision-making. The data obtained from the interviews is available on request to the project steering committee. The interviews covered a range of topics such as household demographics, agricultural production, food consumption, waste generation, income, social attitudes, and perceptions on CB practices. Some questions were tailored to specific segments of the population, while others such as those on household demographics, consumption, awareness, knowledge, support for CB practices, and opinions on eating CB foods, were asked to all respondents.

3.2. Analytical model

We apply a multivariate multiple regression approach. Since our outcome variables were dichotomous in nature, we needed to estimate the multivariate multiple regression as a multivariate probit regression illustrated in Eq. 1. Hence, for this study as defined by Cappellari & Jenkins (2003) a probability of success design measures the likelihood that a desired outcome occurs. Specifically, the probability of success represents the likelihood that CB adoption practices reflect a real-world experience. Additionally, one-way analysis of variance (ANOVA) was used to estimate any statistically significant differences between variables among countries under study.

$$Y_{ij}^{*} = \beta_0 + \beta_j \mathbf{X_i} + \upsilon_{ij} \tag{1}$$

$Y_{ij} = 1 \ if \ Y_{ij}^{*} > 0$ and 0 otherwise

Where Y_{ij}^{*} denotes a latent variable; Y_{ij} is an outcome variable for household $i = 1,\ldots,N$ and outcomes $j = 1,\ldots,M$, β_0 is a constant, and β_j are parameters to be estimated. $\mathbf{X}_i$ is a vector of covariates, and υ_i are error terms assumed to be independently and identically distributed across i but correlated across outcomes j for any household i. A multivariate probit analysis approach has been previously used in other studies (Marenya & Barrett, 2007; Kassie et al. 2013; Teklewold et al. 2013; Kassie et al. 2015) to analyze agricultural practices in Africa. It is possible to achieve unlimited dimensionality since only pairs of outcomes are analyzed during each estimation phase. Additionally, estimator precision is retained as it would have been under the assumptions of the multivariate probit estimation (Mullahy, 2016). Bivariate probit is also specified as the multivariate probit in Eq. 1, only that the bivariate probit estimates two regressions (a pair) at ago (Mullahy, 2016). Stata SE 16.0, a software were used to fulfil analysis (Mullahy, 2017). After analyzing the three CB practices, we identified three possible combinations of practices that households could engage in simultaneously. These combinations were analyzed in phases using the bivariate probit. The first combination involved using organic waste as compost and sorting organic waste from inorganic waste. The second combination involved using organic waste as livestock feed and sorting organic waste. The third combination involved using organic waste as both compost and livestock feed.

3.3. Measurement of outcome variables

The CB practices are discrete dichotomous variables. For instance, if a household utilized organic waste as compost or livestock feed, or sorted organic from inorganic waste, it was assigned a value of 1. Alternatively, if the household did not engage in any of these CB practices independently, a value of 0 was assigned. Subsequently, we ended-up with two possibilities for each household for each outcome. Analyzing dichotomous variables in natural categories; in this case, household engagement in CB practices or not helps limit correlation interferences in reference with Glen (2014) and Khajuria et al. (2022). In this study, several household and contextual characteristics were used as covariates based on literature and field observations. For instance, if a household was growing crops or had access to land, it would determine if the household had the needed space to engage in CB practices, or even the purpose to be served as farming (Lambrecht et al., 2016). Hence, we anticipated that these two covariates could positively influence engagement in CB practices. Access to credit was also expected to positively influence engagement in CB practices, since some activities around these practices require financial liquidity as attested by Holden et al.(2023). Access to technical equipment that can make labor-intensive activities easier, as well as access to markets where raw materials for CB practices can be sourced or CB products can be sold, are expected to have a positive impact on engagement in CB practices. Additionally, mobile phone use can facilitate access to market information, leading to further engagement in CB practices. Having the main source of income as agriculture was also expected to positively influence such engagement, since associated CB products would easily be used in agriculture according to Cheah et al.(2023) and Simbeko et al. (2023). High education levels like vocational and university were expected to influence households towards sorting organic from inorganic waste at household level, since educated heads could easily comprehend CB concepts and thus engage in CB practices. Lower education levels comprise no education, primary, and secondary level were expected to be associated with use of organic waste as compost or livestock feed, because at such low education levels, high paying salaried opportunities would be barely accessible thus committing households to agriculture. This is in accordance with other studies (Holden et al., 2023; Odur-o-Kwarteng et al., 2016; Rahmayanti et al., 2020). CB practices require a lot of labor; hence a larger household size was expected to have a positive impact on these practices. Similarly, older household heads were expected to engage in CB practices more frequently as they were assumed to have more adult children who could provide labor. South African households were expected to engage in CB practices less frequently compared to those in DRC, Ethiopia, and Rwanda due to their minimal daily dependence on subsistence agriculture. This evidence was also fund in other studies (Sekabira et al., 2022; Sharma et al., 2021) in africa.

4. Results

4.1. Cases of innovative Bioeconomic practices introduced in the countries under study

In DR Congo, *Femme et Environnement Sain pour le Développement Durable* (FESDD) organisation have convinced 400 households to sort their household waste in two bags (inorganic and organic). Organic waste is sorted and transported to rural areas for composting. 749 tons of compost have been used by over 430 coffee farmers in the past 2.5 years. The success of this innovation lies in the fact that it does not only improve coffee yields and soil fertility in Kabare, but it also decreases urban insalubrity in the city of Bukavu (RUNRES-DRC, 2023). Additionally, the Démarche *pour une Intéraction entre les Organisations de Bases et Autres Sources de Savoirs* (DIOBASS) organisation is experimenting circular with economy approaches by trying to restore soil nutrients by creating compost with organic household waste. Now, the organic waste is collected from 300 households in Bukavu city and from the Nyawera market, where a lot of waste accumulates. 48 tons of compost are expected to be produced every six months. Most of the farmers hope to increase their production from 0.6 ton to 1 ton of coffee per hectare. GASD (Globale Action for Sustainable Development) is another organisation producing co-compost by recovering organic waste from different sources. 1) household waste; 200 households from Bukavu city, 2) waste from Katana and Kabamba markets, 3) coffee pulps from Cooperative of Planters of coffee in Kabare (CPCK); a coffee farmer cooperative washing stations, as well as 4) human waste from ecological toilets built on the two markets: Katana and Kabamba (RUNRES, 2023; RUNRES-DRC, 2023). This co-composting innovation as present in Fig. 3 represents a great opportunity to increase agricultural production, but also to provide sustainable solutions to the insalubrity problems caused by accumulating urban waste.

Several innovations were introduced (Fig. 4) in Ethiopia. ENMCPA (Egnan Naew Mayet Compost Production Association) association serves as a bridge between waste collectors and compost users, the local banana farmers. Once the composting facility is operational, the enterprise in the city region of Arba Minch plans to process and recycle 1,100 tons of compost per year. Currently, ENMCPA receives municipal biowaste from four women associations. This innovation not only leads to the recycling of municipal organic solid waste but also creates job opportunities for women. The Anjonus Fruit and Vegetable processing Enterprise (AFVPE) produces banana flour from physiologically matured unripen bananas (RUNRES-Ethiopia, 2023). Runres has introduced a recycling system for urine, where a Urine Diverting mobile toilet has been installed in locations with high public frequency, such as bus stations, public parks, and marketplaces to collect source-separated human urine. The collected urine is then transformed into struvite fertilizer, which is seen as a sustainable alternative to urea fertilizer. Additionnally, it is trying to modify the existing public toilets so that they can separate at the source human urine from feces. Finally, the isolated urine is transported daily to the treatment site, where it will be processed into struvite (RUNRES, 2023; RUNRES-Ethiopia, 2023).

Fig. 5 illustrate some keys Bioeconomic practices introduced in Rwanda. In Rwanda, Akanoze is a small-scale cassava-processing unit in Kamonyi that recycles the non-utilized cassava peels, which account for approximately 30 % of the weight of the tubers. Cassava peels have traditionally been disposed of by rotting or burning due to their high levels of cyanide. However, a new process has been developed to make use of these peels. They are now chopped, pressed to extract water, solar-dried, and finally, ground to produce flour. This process makes the peels safe for animal consumption. This flour is sold to a gross retailer as a basis for the manufacturing of animal feed (RUNRES, 2023; RUNRES-Rwanda, 2023). Because animal feed is often imported to Rwanda and sold at a prohibitive price for subsistence farmers, this innovation offers an affordable local source of fiber rich animal feed. Maggot compagny is a Black Soldier Fly (BSF) facility, that upcycles green waste, brewery waste and household waste from the local community. These organic wastes are chopped finely so that they can be fed to BSF larvae (Fig. 5). For approximately 13 to 18 days, the larvae consume waste before being sold to fish and livestock farmers as a source of high-protein animal feed, primarily for poultry and pigs. Because animal feed is often imported to Rwanda and sold at a prohibitive price for subsistence farmers, this innovation offers an affordable, local alternative that also provides economic opportunities within the community. COPED (Company for Protection of Environment and Development) is a solid waste management company that operates in the larger Kigali region, is piloting a program with the support of RUNRES to sort waste at the household level in the local community. Once sorted, the organic waste is transported to the COPED composting facility (RUNRES-Rwanda, 2023). Three different qualities of compost are proposed to satisfy different types of clients: from a grade 1 for gardeners, to grade 2 for annual crop farmers, to grade 3 for perennial crop farmers. Hence, in this local area, sorting waste at household level is a new and needed practice to produce high quality compost.

In South-Africa a public private partnership was established with a private actor (Duzi Turf), a public utility (Umgeni Water), and a local municipality (Msunduzi Municipality) to explore the potential of co-compost production at a municipal scale. The private company co-composts the garden/green waste and dewatered sewage sludge provided by the municipality and public utility, respectively. The private company is conveniently located next to the landfill site and the public utility in order to facilitate the collection of the materials (RUNRES South - Africa, 2023). The garden waste is then: 1) chipped to the

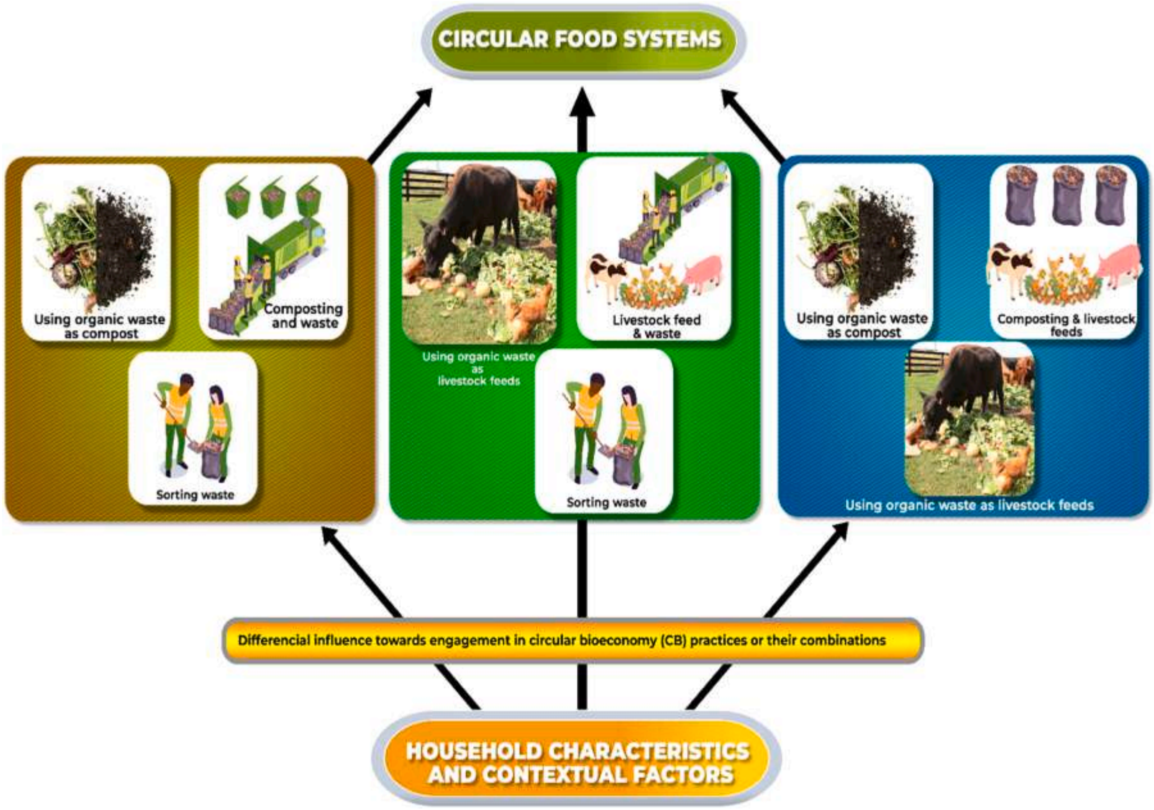

Fig. 1. Author's Conceptual framework on linkages between household characteristics, CB practices, and circular food systems.

required structural consistency, 2) combined with sludge from a Waste Water Treatment Plant (WWTP), and 3) composted in windrows. In addition to supporting the production of turf grass, this co-compost will benefit the farmer-cooperatives from the nearby Sobantu community by improving the soil fertility management and yields. Umgeni Water, a state-owned entity, envisions installing an Integrated Decentralized Wastewater Treatment System (DEWATS) and pour flush urine diversion system as a sustainable onsite sanitation and resource recovery system in a rural school. The innovation aims to: 1) address sanitation management challenges at a school serving approximately 500 students (Sikhululiwe School) and 2) contribute to improved livelihoods of people in Vulindlela community. Currently, most of the technological options in the ecological sanitation sector face bureaucratic limitations concerning reuse of human excreta (RUNRES South-Africa, 2023). Therefore, this pilot scale innovation will be useful to build data-based evidence to help influence the regulations/policies that stymie reuse of human waste and water/wastewater treatment sludge at large scale (RUNRES, 2023). This innovation Fig. 6 has the potential to alleviate the sanitation challenge presented by rapidly filling pit latrines, create several employment opportunities while at the same time improving the productivity of local farming operations. The enhanced biochar produced would also be sold to the local community and in the nearest urban centres.

4.2. Descriptive analysis and variables modalities

From Table 1, the most dominant CB practice was sorting of organic waste from inorganic, practiced by 58 % of the sample, followed by using organic waste as compost (41 %), and least was using organic waste as livestock feeds (19 %). Scholar emphasises that, in households with livestock, which often use uneaten food for animal feed, the trend is that it created about more food waste than other households with less livestock (Qi et al., 2021). We postulate that intensified livestock production led to less uneaten food being used as animal feed and, in response, led to more efficient household consumption including less discarded food. Most of the sample (58 %) was also engaged in growing crops, and 72 % had access to land. On average, each household had 8 persons, with heads being dominantly male (77 %), and aged 45 years with an average annual income of 1,476 USD.

Most household heads (37 %) were only formally educated up to primary level, with another 29 % not going beyond secondary, while 10 % never attended formal school at all and the one-way anova analysis is signficant among countries *($p<.001$)*. 5 % had attained vocational education, and 18 % attended university, implying that about 22 % had attained tertiary education. Interestingly, a larger proportion of the sample (56 %) had access to credit, markets (51 %), used technical equipment (56 %), and used mobile phones (87 %). Salaried employment and casual labor were the main source of income for most of the sample (37 %), followed by agriculture (28 %), then grants remittances and pensions (20 %), and least was self-employment and businesses (9 %). About 7 % of the sample had no employment. And the difference is signficant accross countries *($p<.001$)*.

4.3. Determinants of success engagement in circular bioeconomy practices

In Table 2, we present determinants of various circular bioeconomy (CB) practices estimated in pairs, to empirically understand what combinations of CB practices would be more likely to success at household level, conditioned to respective household characteristics. First, we present predicted probabilities of success for these CB practices' combinations, and then later present those household characteristics that could successfully favor these respective CB practices. From Table 2, all the possible three CB practices' combinations (using organic waste as compost and sorting waste = combination 1; using organic waste as livestock feed and sorting waste = combination 2; and using organic waste as compost and as livestock feed = combination 3) do have a positive and significant likelihood to succeed at smallholder household level. However, the magnitude of this likelihood differs, for instance,

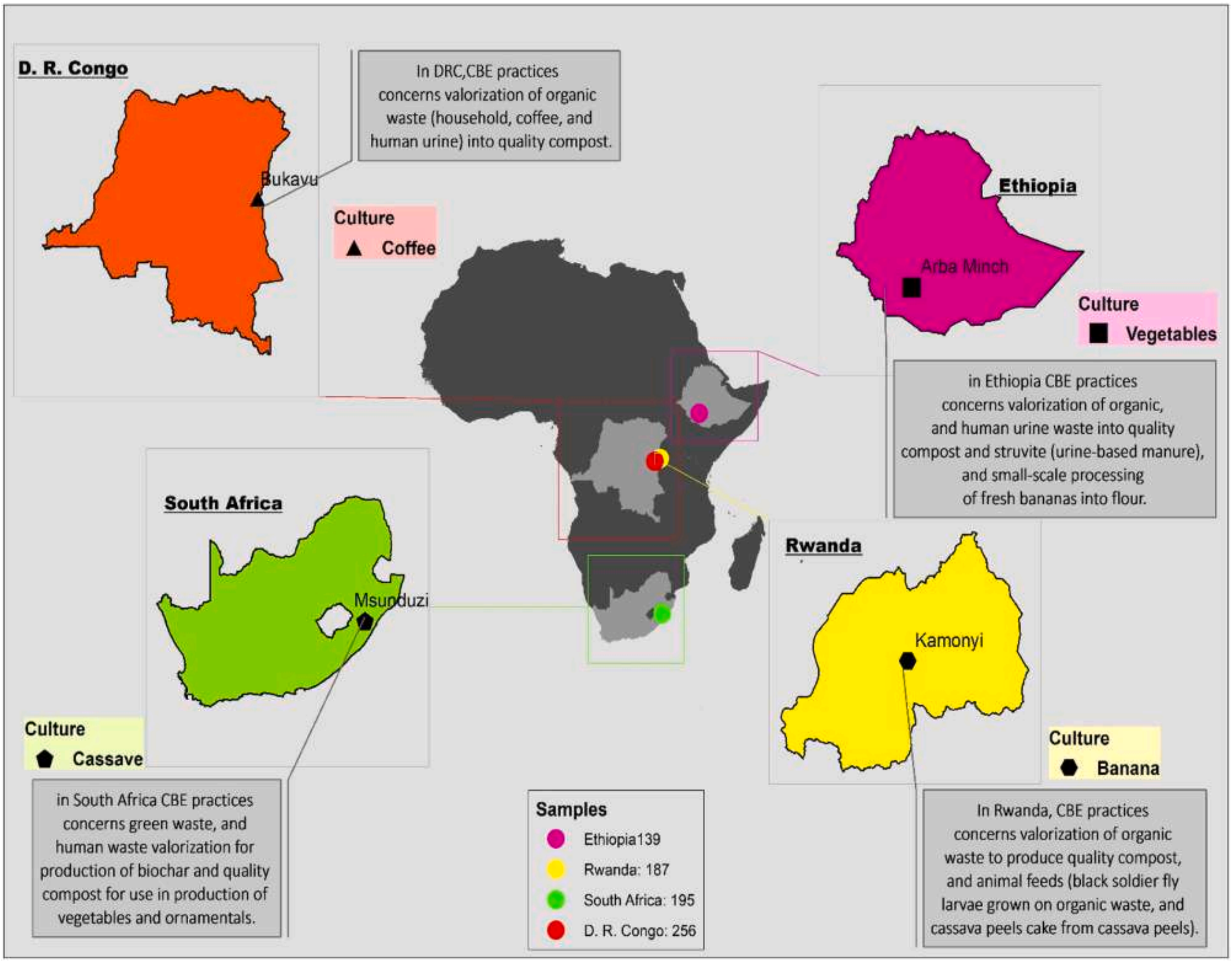

Fig. 2. CBE practices in city-regions in four African; coffee in DRC, bananas in Ethiopia, cassava in Rwanda, and vegetables in South Africa.

Fig. 3. (A) Covered compost piles at the Mudaka waste processing center, (B) Sieving and packaging of the produced compost at Mudaka and (C) Waste unloading and sorting at Mulungu waste processing center.

currently combination 1 has a possibility of nearly 31 % to be practiced, while that of combination 2, and 3 is nearly 17 % , and 11 % respectively. However, household factors do differentially influence the success of CB practices in these combinations, and we elaborate these influences below.

The results indicate that households engaged in crop farming were more likely to participate in all three CB practices than those employed in salaried or casual jobs, albeit with varying likelihoods. The most practiced CB was using organic waste as compost (36 %), followed by sorting (22 %), and using organic waste as livestock feed (17 %). Additionally, land access was found to be a positive factor that influenced practicing of all three CB practices. Households that have access to land were 8 % , 6 % , and 12 % more likely to use organic waste as compost or as livestock feed, and sort waste respectively. However, other factors are not associated with these CB practices in a uniform direction or comparatively important magnitudes. For instance, annual household income was only significantly associated with using organic waste as compost. Each additional 100 USD on annual income (*Chi2. 340, $p<.001$*), was associated with a reduction of 10 % in the likelihood of a household using organic waste as compost. On the other hand, households that had access to credit were more likely by 9 % , to engage in sorting organic from inorganic waste. Surprisingly, use of mobile

Fig. 4. (D) Sieved and packed organic compost ready to be sold to the local farmers, (E) Matured unripen banana fingers cleaning and detaching, (F) the final product sold on the market: packed banana flour and(G) Struvite reactor of Mobile toilet used for source separated urine collection.

Fig. 5. (H) A cooperative of women are employed on a daily basis to peel cassava, (I) Employees bringing the organic waste collected from the market to a vegetable cutter machine, (J) he Black Soldier Fly (BSF) larvae are fed on the chopped organic waste (and brewing waste sourced from a local brewery), (K) Waste is sorted at the household level between organic (green bag) and inorganic (blue bag) and (L) At the compost production site, men are employed to remove remaining inorganic components and to prepare and maintain the compost heaps.

Fig. 6. (M) The windrows are composed by a mixture of organic waste and sewage sludge. For this reason, the process is called co-composting and not only composting, (N) filled up toilet in Vulindlela community and (O) Garden waste is chipped before mixing with the sewage sludge.

phones was negatively associated to all three CB practices, and associations were significant about using organic waste as livestock feed (14 %) and sorting waste (9 %). As expected, market access was associated with a positive likelihood to use organic waste as compost, or as livestock feed (7 %), and sorting waste (7 %) and significant *($p<.001$)*, although the association was insignificant for using organic waste as compost. Thus, as shown in Fig. 7 below, major socio-economic parameters used in this paper have contributed successfully to the likelihood of using organic waste as compost in a significant way (taking all things evenly). The red horizontal line at the zero value of the y-axis separates the area between the upper and lower confidence bounds. Grid lines indicate each household characteristic's predictive margin.

Uninterestingly but not surprisingly, households that had other avenues like salaried employment, casual labor, self-employment, business, remittances pensions and grants, as main sources of income compared to being in agriculture, were all significantly less likely to engage in any of the three CB practices. The low likelihood of engaging in any of three CB practices for the multiple income group were between 9 to 38 % for using organic waste as compost, 8 to 24 % for using organic waste as livestock feed, and 16 to 28 % for sorting waste. In a similar regard, households that had access to technical equipment were less likely to use organic waste as compost, or as livestock feed – but were insignificantly more likely to engage in sorting waste. The association was only significant with using organic waste as compost (reduced likelihood by 10 %). Compared to having no education, any education level did not significantly associate with using organic waste as compost, despite a positive association. Hence, as shown in Fig. 8 below, major socio-economic parameters used in context of this paper have

Table 1
Descriptive analysis and variables modalities used in the study.

Variables	Mean/Percent (standard deviation)					
Country	Rwanda (N=187)	South Africa (N=195)	DRC (N=256)	Ethiopia (N=139)	All (N=777)	(One-Way Anova test)
Uses organic waste as:						
Compost (dummy)	75.9	34.9	38.3	6.47	40.8	(166.89)***
Livestock feed (dummy)	27.3	33.8	3.52	15.8	19.0	(126.38)***
Sort organic waste (dummy)	68.4	61.5	39.5	71.9	57.8	(56.53)***
Grows crops (dummy)	69.5	95.4	43.0	18.7	58.2	(234.17)***
Access to land (dummy)	67.9	86.2	64.5	70.5	71.8	(28.18)***
Age of household head (years)	39.56	51.61	45.58	41.91	44.99	(24.32)***
	(12.13)	(15.89)	(15.28)	(14.27)	(15.21)	
Household size (persons)	5.942	7.395	9.409	7.811	7.783	(44.23)***
	(2.718)	(3.181)	(2.522)	(2.944)	(3.108)	
Annual income (USD)	997.3	2227	1019	1066	1476	(9.38)***
	(3652)	(7807)	(1959)	(2383)	(5418)	
Access to credit (dummy)	58.3	54.4	44.1	74.1	55.5	(33.53)***
Uses mobile phone (dummy)	83.4	92.3	85.2	88.5	87.1	(8.07)*
Male household head (dummy)	86.1	49.7	92.2	76.3	77.2	(124.74)***
Access to markets (dummy)	67.4	52.8	30.1	66.2	51.2	(78.0)***
Access tech. equip. (dummy)	56.2	72.3	30.9	78.4	55.9	(114.97)***
Main income source						
Agriculture	47.6	7.18	33.2	23.7	28.4	(81.37)***
Salaried / casual labor	42.8	21.0	33.2	41.7	33.9	(24.83)***
Self-employment / business	1.07	3.08	19.1	10.8	9.27	(53.9)***
Grants, Remittances or pension	4.28	58.5	1.17	21.6	19.9	(266.62)***
Hand craft or Other employment	2.67	1.03	1.17	0.72	1.42	(2.92)
No employment at all	1.60	9.23	12.1	1.44	6.95	(26.9)***
Education level						
None at all	5.35	8.21	8.20	23.7	10.3	(34.3)***
Primary	67.4	38.5	19.5	28.1	37.3	(112.06)***
Secondary	17.1	41.5	32.8	22.3	29.3	(32.29)***
Vocational	0.54	3.08	3.52	15.1	4.76	(42.27)***
University	9.63	7.69	35.6	10.8	17.9	(81.60)***
Education higher levels	0.00	1.03	0.39	0.00	0.39	(3.3)

In parentheses are standard deviations

contributed successfully to the likelihood of sorting organic waste from inorganic in a significant way (taking all things evenly). The red horizontal line at the zero value of the y-axis, separating area between the upper and lower confidence bounds and the grid lines indicate each household characteristics with it predictive margin.

In fact, the association with university level was negative. About using organic waste as livestock feeds, again low education levels (primary by 8 % , and secondary by 9 %) households were the ones significantly more likely to engage in the CB practice. Again, the association with university graduates was negative. Moreover, with regards to sorting waste, all households at any education level were less likely to sort waste. In fact, the negative association was significant for more educated households (university by 20 % for each level). In comparison to Rwanda, households in other countries were In fact, the negative association was significant for more educated households (vocation or university by 20 % for each level). In comparison to Rwanda, households in other countries were significantly less inclined to use organic waste as compost, with South Africa showing a 37 % decrease, DRC showing a 40 % decrease, and Ethiopia showing a 52 % decrease. However, households in South Africa were 11 % more likely to use organic waste as livestock feed, while those in DRC were 17 % less likely. On the other hand, households in Ethiopia were significantly more likely by 14 % to sort waste. Therefore, as shown in Fig. 9 below, major socio-economic parameters used in this paper have contributed successfully to the likelihood of using organic waste as livestock feed in a significant way (taking all things evenly). The red horizontal line at the 0 value of the y-axis separates the area between the upper and lower confidence bounds and indicates each household characteristic's predictive margin on the grid lines.

5. Discussions

As attested in other studies (GGGI, 2018; Krütli et al. 2018; Kaza et al. 2018; GGGI, 2020). The dominance of sorting is not surprising since urban households that are asked by waste can also easily practice these collectors to sort waste so to ease waste management. Using organic waste as compost or livestock feed is mostly possible in rural or some peri-urban areas where crop and livestock farming are relatively more feasible due to land availability. However, livestock farming is more capital-intensive, requiring the purchase of livestock, housing, daily feeding, care taking, etc. As a result, it is not surprising that it is the least commonly practiced CB activity. It is not surprising that most of the sample was involved in crop farming, since the identification of respondents was based on strategic food commodity value chains (cassava in Rwanda, coffee in DRC, bananas in Ethiopia, and vegetables in South Africa). Moreover, the higher proportion that had access to land than those engaged in crop farming, indicates that there were indeed other actors in these value chains engaged in other activities, other than crop farming. Sekabira et al. (2021) found that coffee and cassava value chains in DRC and Rwanda respectively were complete with all actors. Male dominance of household headship in Africa is more like a tradition for patrilinear groups, and has also been confirmed in other gender-disaggregated data studies (Sekabira & Qaim, 2017). However, in South Africa, where economic development is more pronounced, and usually outweighs traditions, the proportion of male heads is just about half. Scholars (Lange et al., 2022; Poswa, 2004) argue that waste management in South Africa has largely overlooked the social and economic dimensions of household life, instead focusing on functional waste collection. As an integral part of the design of a waste treatment plan, specific importance should be given to the gender dimension of the collection system and material selection.

The relatively high proportion of tertiary education, as said before,

Table 2
Multivariate regressions for household characteristics on circular bioeconomy practices.

Variables	Marginal effects after multivariate probit estimates via bivariate probit		
Models	(1) Uses organic waste as compost	(2) Uses organic waste as livestock feed	(3) Sorts organic waste from inorganic
Socio economics and demographic caracteristics			
Growing crops (Dummy)	0.360***	0.174***	0.218***
	(0.046)	(0.036)	(0.059)
Access to land (Dummy)	0.075**	0.060*	0.124***
	(0.035)	(0.035)	(0.044)
Age of household head (years)	0.002	-0.001	-0.001
	(0.001)	(0.001)	(0.001)
Household size (persons)	0.004	0.002	-0.001
	(0.004)	(0.005)	(0.006)
Annual household income (USD)	-0.001***	-4.5×10^{-5}	-2.4×10^{-4}
	(2×10^{-4})	(2×10^{-4})	(3×10^{-4})
Access to Credit (Dummy)	0.009	0.006	0.091***
	(0.027)	(0.028)	(0.035)
Own and uses mobile phone (Dummy)	-0.016	-0.139***	-0.092*
	(0.045)	(0.046)	(0.053)
Male household head (Dummy)	-0.039	0.016	-0.053
	(0.034)	(0.031)	(0.042)
Access to markets (Dummy)	0.005	0.070***	0.065*
	(0.029)	(0.027)	(0.037)
Access to technical equipment (Dummy)	-0.101***	-0.027	0.027
	(0.029)	(0.032)	(0.040)
Main income source compared to being Agriculture			
Salaried or casual employment	-0.093*	-0.037	0.059
	(0.050)	(0.041)	(0.053)
Self or business employment	-0.281***	-0.002	-0.163**
	(0.071)	(0.073)	(0.078)
Grants, Remittances, or allowances	-0.207***	-0.080*	-0.007
	(0.059)	(0.045)	(0.065)
Hand craft or other employment	-0.163	-0.236***	-0.276*
	(0.125)	(0.029)	(0.149)
Having no employment	-0.381***	-0.195***	-0.087
	(0.075)	(0.050)	(0.107)
Education level compared to having no education			
Primary	0.019	0.079**	-0.030
	(0.048)	(0.039)	(0.059)
Secondary	0.062	0.090**	-0.079
	(0.052)	(0.045)	(0.064)
Vocational education	0.039	0.078	-0.203**
	(0.086)	(0.076)	(0.093)
University	-0.024	-0.021	-0.203***
	(0.060)	(0.053)	(0.077)
Education higher levels	-0.379	-0.125***	-0.655***
	(6.267)	(0.034)	(0.057)
Country compared to Rwanda			
South Africa	-0.366***	0.105*	-0.089
	(0.051)	(0.056)	(0.064)
DRC	-0.399***	-0.172***	-0.1 16
	(0.068)	(0.037)	(0.079)
Ethiopia	-0.523***	0.041	0.137***
	(0.056)	(0.055)	(0.052)
Observations	777	777	777
Wald chi2 (model pairs)	Organic waste used as livestock feed, & sorts organic waste		257.36***
	Organic waste used as compost, & as livestock feed		339.99***
	Organic waste used as compost, & sorts organic waste		371.43***
Probability	(Organic waste used as compost=1, & sorts organic from inorganic=1)=CBN 1		0.309***
	(Organic waste used as feed livestock=1, & sorts organic from inorganic =1)=CBN 2		0.166***
	(Organic waste used as compost=1, & organic used as feed livestock=1)=CBN 3		0.106***

Standard errors in parentheses;
*** $p<0.01$,
** $p<0.05$,
* $p<0.1$; CBN is combination.

may be explained by using a diverse smallholder sample, that isn't comprised of smallholder farmers only, but also partially constituted by smallholder processors, traders, and retailers in considered food value chains (Liu et al., 2023). Moreover, addition of these other types of smallholder actors in food value chains from more developed countries like South Africa, does also explain the relatively higher annual incomes. Statista (2021) has reported the GDP per capita of South Africa to be 5742 US dollars in 2020, way above by at least three times. According to researchers (Koppmair et al. 2017; Sekabira & Qaim; 2017; Sekabira et al. 2021), the household size and age of household heads reported here are largely coherent with literatures on smallholder households. The use of technical equipment, mobile phones, access to credit, and markets suggests that value chains are functioning relatively well. Consumers can access inputs and food commodity products through these markets, and technical equipment can enhance the value of these products. Credit access can help provide financial liquidity to operations within the value chains, while heavy mobile phone use facilitates communication and access to reliable market information, and competitive prices and this is in accordance with other studies (Aker & Mbiti, 2010; Sekabira & Qaim, 2017). A significant number of individuals, apart from farmers, are employed in various roles such as processors, retailers, laborers, and intermediaries within the food value chains and waste management sections. This explains why salaried employment and casual labor remain the primary sources of income for most of the sample.

The highest current CB practices' combination possibility is 31 % for combination 1 (sorting and composting). This finding suggests that significant amounts of organic waste are not currently reused in crop and livestock farming. These results also imply that combination 1 (sorting and composting), is currently the dominant CB practices' combination in the study regions, as was also established by Sekabira et al. (2021). The CB practice of composting in this combination context are characteristic of subsistence agriculture have been proved to be less viable towards household income and food security by Sekabira & Kantengwa, (2021a; 2021b). Food and economic viability is key to sustaining CB practices in food systems while enhancing circularity. The currently low success probabilities of combination 2, could also be explained by the fact that there are more households engaged in crop farming by default than livestock farming.Thus, barely having substantial effects towards better household income and food security (Sekabira & Kantengwa, 2021a; 2021b). To move smallholder food systems away from subsistence farming, combination 1 (sorting and composting) that prioritizes crop farming can be exchanged for combinations 2 and 3 that focus on both crop and livestock farming. Combination 2 still provides animal excreta for composting in crop farming, while combination 3 (composting and livestock feed) is less likely to succeed due to competing uses of organic waste. However, if sorting is combined with either composting or livestock feed, it provides raw materials (organic waste) for reuse in any of the other two practices. The success of these combinations at the household level can be explained by several underlying household characteristics, which we discuss below.

Crop farming being associated positively with all CB practices is not

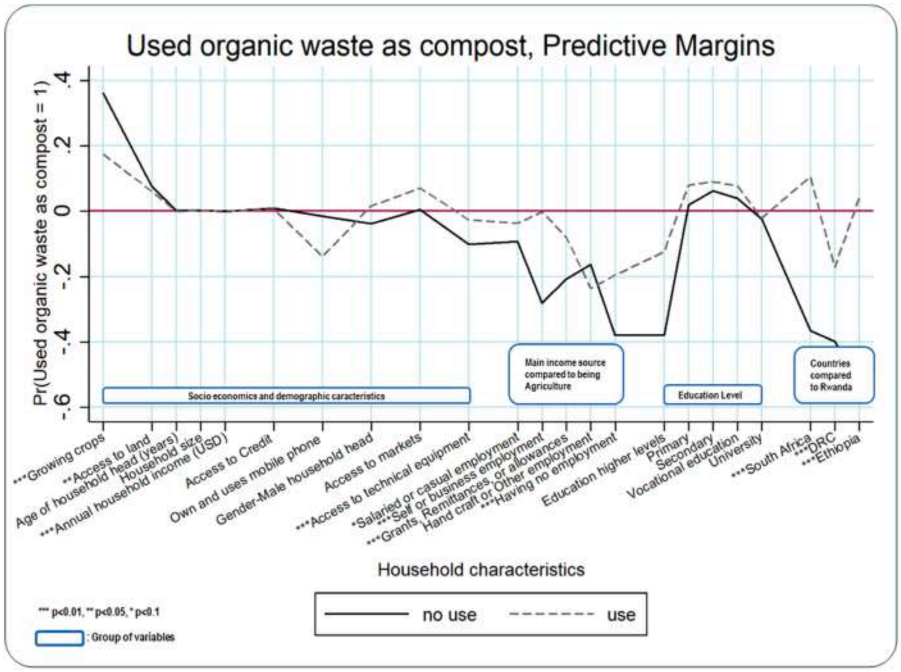

Fig. 7. Predictive margins of using organic waste as compost.

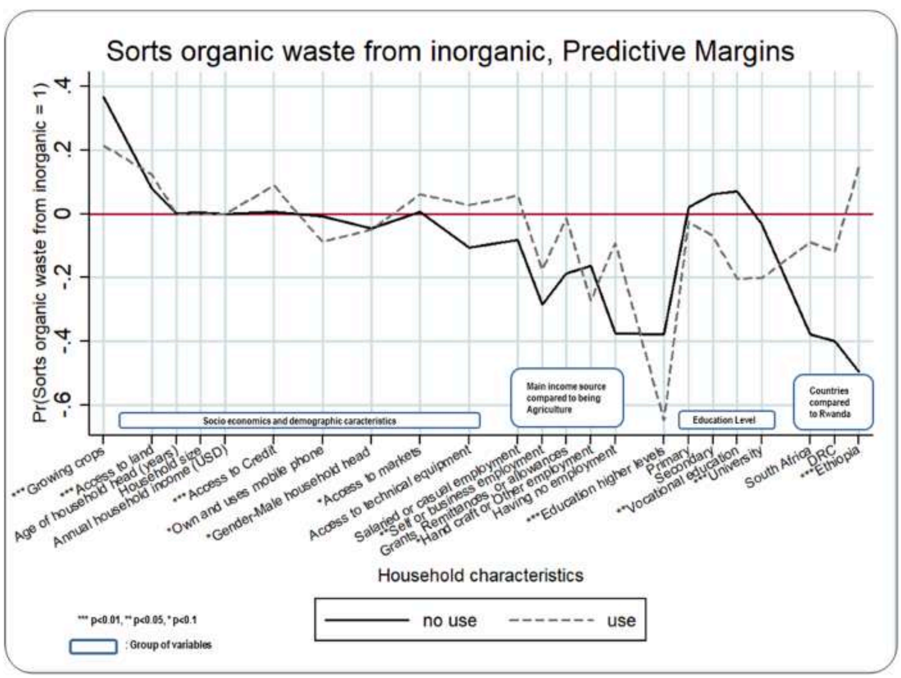

Fig. 8. Predictive margins of sorting waste from inorganic.

surprising. Crop farmers would need compost to improve soil nutrients and structure, and sometimes participate in livestock farming to diversify their income and food sources. For GGGI (2018; 2019; 2020) sorting waste provides the organic waste that is used in composting or feeding livestock. Moreover, crop farmers can as well be interested in organic manure from animal excreta. It is also clear that most crop farmers would likely practice composting compared to all other CB practices. Currently, compost making requires relatively minimal resources (dumping organic waste on farm to naturally decompose. Proved by Sekabira & Kantengwa (2021a; 2021b). Such simplistic and ineffective way of compost making could explain the current low returns from composting towards household income and food security. To successfully implement the three CB practices, it is essential to have sufficient space. This can only be possible if a household has access to land. The land can be utilized for various purposes, such as composting organic waste, separating organic waste from inorganic waste, or keeping livestock to feed on the separated organic waste. Therefore, having access to land is crucial for the effective implementation of CB practices. As found by Frankema (2014) and Pelster et al. (2017) most African agriculture is dependent on natural provisions without significant use of purchased inputs, which is typical of subsistence agriculture. Using compost is one of the natural ways through which smallholders enhance soil nutrients

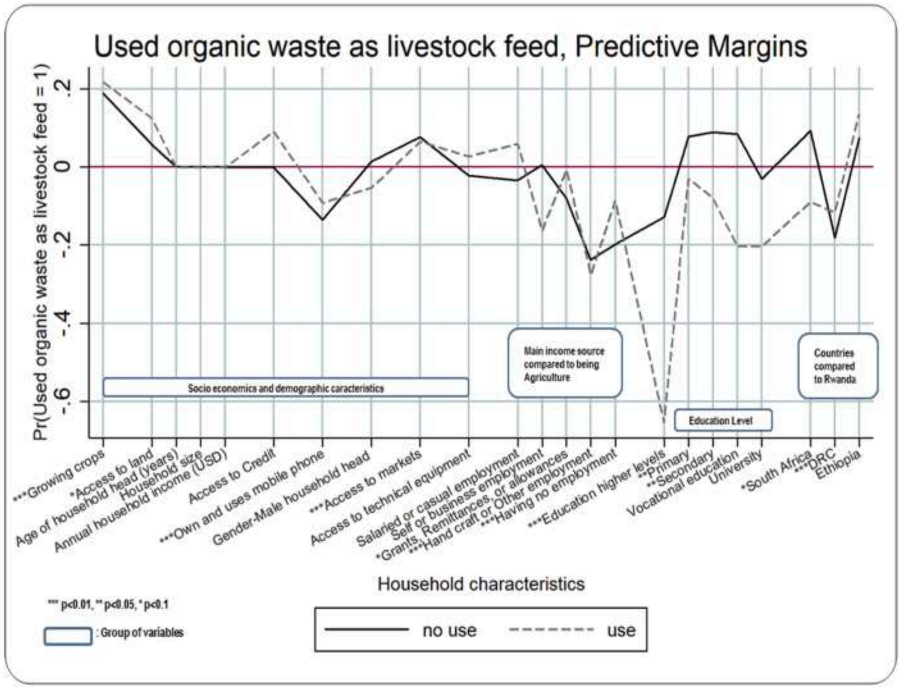

Fig. 9. Predictive margins of using organic waste as livestock feed.

and structure (Klammsteiner et al. 2020). As farmers earn higher incomes, they tend to shift away from subsistence farming and start buying industrial inputs like inorganic fertilizers. In some cases, they may even stop farming altogether and opt for other occupations. In peri-urban and urban areas, waste is often collected and sorted by women, children, or male youths. The intent is usually to identify better quality waste that can either be sold to waste recyclers like metal, paper, and plastic, or sold to urban livestock farmers as feeds for instance food waste. For scholars (Krütli et al. 2018; Kaza et al. 2018; GGGI, 2018; 2019; 2020), these activities are labor intensive and require daily financial liquidity for transport, communication, packaging etc.. Therefore, access to credit would strongly facilitate sorting.

The lack of significance of mobile phones may be due to the existing waste management infrastructure. Virtual communication that is facilitated by mobile phones may not be so essential, more so that physical movement is warranted to sort and transport such waste for reuse (GGGI, 2018; 2020). Also, a substantial amount of waste is generated in market places, where general merchandise markets produce a lot of paper, metal, plastic etc. which is usually collected and resold to waste recycling companies (GGGI, 2018). Food markets on the other hand generate a lot of food waste, that is mostly sold immediately to livestock farmers as feeds, or kept in dump sites to decompose and be sold later as compost (GGGI, 2018; 2019). Without access to markets such access to abundant waste resources could be impossible for willing households.

It is evident from the negative correlation observed between circular bioeconomy practices and other sources of income apart from agriculture that only households relying predominantly on agriculture in the study regions and other parts of Africa are inclined to participate in circular bioeconomy activities. This agrees with Sekabira et al. (2021), who found that farmers were the only food commodities value chains actors that were practicing any forms of circular bioeconomy dominantly. Therefore, CB innovators, must work out modalities to interest other actors in food value chains towards circular food systems, especially consumers who generate more waste due to their comparatively higher consumption (better incomes) in areas (urban) further from agricultural lands (rural) (Krütli et al. 2018; Kaza et al. 2018; GGGI, 2020). Establishing a sustainable circular food system would need all actors to play an active role regardless of their income status (Dasgupta, 2021).

Even though, actors that are mostly earning from other sectors other than agriculture, may have no land for crop and livestock farming, they must be willing to at least sort organic from inorganic waste at household level, which would make it easier for recycling and reuse as compost, or as livestock feed. Scholars (El-Chichakli et al. 2016; Jurgilevich et al. 2016; Geissdoerfer et al. 2017; Carus & Dammer, 2018; EMF, 2019; Issa et al. 2019; Sekabira et al. 2021; Feleke et al. 2021) attest that activeness of all actors will effectively help close nutrient loops, and establish circularity which will enhance the resilience and sustainability of food systems. As highlighted earlier by Frankema (2014) and Pelster et al. (2017), African agriculture is minimally dependent on purchased inputs, implying that it is as well less mechanized. A household that becomes able to financially invest in technical equipment or other purchased inputs, is likely to abandon traditional practices, which usually includes composting. Seeking industrial inputs and better practices is usually intended to increase productivity (Shiferaw et al. 2009). Therefore, CB innovations to sustainably establish a circular food system must avail CB practices that are competitive in producing quality products (compost or feeds) that substantially increase farm productivity.

Even though only lowly educated households are more likely to participate in using organic waste as livestock feed and the insignificant correlation between education and using organic waste as compost, it might still indicate a significant lack of awareness among Africa's elite about the advantages of circular food systems. In another perspective, it can simply highlight the fact that, barely educated actors (Dorward et al. 2004) dominate Africa's agriculture production component. The educated persons are generally less interested to engage in CB practices like sorting waste that could help ease recycling and reuse of organic waste in agricultural production. With regards to country effects, Rwanda has the second highest population density (523 inhabitants/km^2) in Africa after Mauritius (Macrotrends, 2021). Therefore, the environmental nuisance that emanates from leaving waste non-recycled in open dumpsites closer to homesteads, could have posed a bigger health risk, thus justifying stricter policy advocacy to dump waste in farmlands. In Rwanda's urban areas, there are also strong policy instruments enforcing households to pay for waste collection that is in the end dumped in rural areas where farmers can easily access it. Using waste as compost would also be a cheaper option as it generally requires households to only dump waste onto their farms where it decomposes. Sekabira & Kantengwa (2021a), find use of organic waste as livestock feed to be positively and significantly associated with household incomes. Therefore, it is not surprising that households in South Africa where the economy is more developed, and households earning higher incomes, were more likely to invest in capital intensive and moneymaking agricultural components like livestock farming. The higher likelihood for Ethiopian households to sort waste could be explained by stronger traditional social and cultural values.

6. Robustness and limitations of the study

We estimate regressions on determinants of engagment in CB practices using multivariate probit model via bivariate probit approaches, and confirm that directions and magnitudes of coefficients are consistently comparable, as asserted by Mullahy (2016). Therefore, we confirm that our results are consistent, reliable, and robust considering the two approaches of discrete multivariate multiple regressions analysis. We chose to present and discuss only bivariate probit results because it was much easier to compute marginal effects of each covariate for each outcome. Additionally, the marginal effects were consistent irrespective of which combination outcomes were paired. However, we must note that our outcomes were measured as discrete dichotomous variables, only assessing the incidences of engagement in CB practices. This means that we were limited in our ability to capture extents of engagement in each CB practice quantitatively, as they could also be measured as continuous dichotomous variables. This was a key limitation, but we were constrained by data availability. Nevertheless, we are optimistic that our categorical analysis of CB practices lays a very firm foundation for more robust quantitative analyses in the future. It also gives distinct predictions of what could naturally happen about combinations of CB practices being discretely possible for smallholder households. In summary, while there were limitations in our study, we believe that our analysis provides valuable insights for future research in this area. Moreover, categorical analysis eliminates interferences and ambiguity to drawing clear correlations and this corresponding to the Glen, (2014) findings.

7. Conclusions with policy recommendations

Understanding how a CB can easily be established within African food systems' context – especially at smallholder household level, is critical to realizing the intended circular food systems that would propel Africa towards attainment of resilient and sustainable food systems, and thus attainment of strategic SDGs of the UN's 2030 agenda. A third combination of practices could be the reason for its minimal chances of success. Therefore, CB innovations aiming for higher probabilities of success (uptake) among smallholders in establishing circular food systems in Africa may need to focus on practice combinations that involve sorting organic from inorganic waste and using organic waste as compost. It is important to ensure that the chosen combination of practices results in the intended benefits for smallholders such as improved farm productivity and better household incomes. However, it is essential to ensure that the selected combination of practices delivers the multiple intended benefits for smallholders, including improved farm productivity and better household incomes. Future research should investigate the productivity and household welfare affects of the chosen combination. The competitiveness in raw materials in the third combination could explain its minimal chances to succeed. Therefore, CB innovations, for higher probabilities of success (uptake) among smallholders in establishing circular food systems in Africa, may need to focus on combinations of practices that entail sorting of organic from inorganic waste, and using organic waste as compost. It is important to ensure that the combination of practices chosen delivers intended benefits for smallholders such as farm productivity and better household incomes. Future research should address the productivity and household welfare influences of the chosen combination of practices.

CRediT authorship contribution statement

Haruna Sekabira: Conceptualization, Formal analysis, Data curation, Methodology, Investigation, Writing – original draft, Writing – review & editing, Project administration, Resources, Software, Supervision, Validation, Visualization. **Guy Simbeko:** Conceptualization, Formal analysis, Data curation, Methodology, Investigation, Writing – original draft, Writing – review & editing, Project administration, Resources, Software, Supervision, Validation, Visualization. **Shiferaw Feleke:** Writing – review & editing, Project administration, Resources, Software, Supervision, Validation, Visualization. **Victor Manyong:** Writing – review & editing, Project administration, Resources, Software, Supervision, Validation, Visualization. **Leonhard Späth:** Writing – review & editing, Project administration, Resources, Software, Supervision, Validation, Visualization. **Pius Krütli:** Writing – review & editing, Project administration, Resources, Software, Supervision, Validation, Visualization. **Bernard Vanlauwe:** Writing – review & editing, Project administration, Resources, Software, Supervision, Validation, Visualization. **Kokou Kintche:** Writing – review & editing, Project administration, Resources, Software, Supervision, Validation, Visualization. **Benjamin Wilde:** Writing – review & editing, Project administration, Resources, Software, Supervision, Validation, Visualization. **Johan Six:** Funding acquisition, Writing – review & editing, Project administration, Resources, Software, Supervision, Validation, Visualization.

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.

Data availability

Data will be made available on request.

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