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ECONOMIC DETERMINANTS OF INDUSTRIAL SYMBIOSIS ON THE MICRO-LEVEL IN SUB-SAHARAN AFRICA. A CASE STUDY FROM UGANDA

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Abstract

Sub-Saharan Africa faces serious challenges related to waste management due to increasing population, consumption, and industrialization ambitions pursued by governments seeking economic development. This paper contributes to research on waste utilization in the region through a case study of industrial symbiosis in Uganda. More specifically, it focuses on the different cost items of waste suppliers of an eco-farm based on a fitness condition equation, including costs of landfilling, transportation, handling, pre-processing, storage, and the waste selling price. Uncovering these elements on the micro level may inform policymakers on how to incentivize industrial symbiosis and help its implementation in an economically feasible way. Data for this research was collected via company visits, semi-structured interviews, and participant observations during two research trips in 2021 and 2022. The results indicate that the additional revenue from selling waste is the least important item in the rationale for IS. In most cases, the potential for reducing landfilling costs motivates companies to participate in IS. The high difference in the other cost items calls for a case-by-case rather than a standardized policy intervention.

Keywords

waste, industrial symbiosis, integrated farming systems, circular economy, Sub-Saharan Africa

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1. Introduction

Older and newer generations of scholars have produced numerous papers touching on how to change or break out from the take-make-use-dispose logic of the linear economy (Erkman, 1997; Korhonen, 2004; Nielsen, 2007; Geissdoerfer et al., 2017; Homrich et al., 2018). Many argue that the functioning of the linear economy is unsustainable. As one potential alternative, the circular economy has recently received intense scholarly and popular attention and has already been put into practice by many entrepreneurs worldwide.

However, Sub-Saharan Africa (SSA) has been relatively underrepresented in these efforts. This provides essential opportunities, not only because of the region's 'underdevelopment' but also because many argue that Africa has better chances to adopt circular economy practices due to its lower embeddedness and dependency on linear models (Lemille, 2020). This neglect is also problematic as the continent faces numerous worrying trends. Increasing population (UN, 2019), consumption and waste generation (Kazat et al., 2018; Hornweeg et al., 2013), low economic and agricultural productivity (Bationo et al., 2006), combined with climate change vulnerability (Baarsch et al., 2020), result in severe risks for food security, societal stability, and environmental and economic sustainability (HLPE, 2013). In addition, African governments pursue economic development through industrialization ambitions. Since 2008, the majority of African countries have adopted formal industrial development strategies (WIR, 2018, p. 128). Uganda, for example, introduced a new national industrial policy in 2020 that aims to increase the industrial contribution to GDP by 2030 (MTIC, 2020, p. XII). Consequently, further industrialization seems inevitable, with increased waste generation. Therefore, a better understanding of how industrialization could occur with less waste generation and more efficient resource use is essential; thus, it is the scope of this study.

One common pattern of existing research about waste utilization in SSA is that they do not consider the role of economic factors and incentives. This is a clearly noticeable and unfortunate research gap, especially because the micro-level dynamics of waste utilization have already been conceptualized and modelled as industrial symbiosis (IS) (Chertow, 2000; Boons et al., 2011; Despeisse et al., 2012; Demartini et al., 2018 and Bertani et al., 2019). Its deeper understanding can inspire policy-making on the local level. Moreover, several ongoing experiments with circular models and waste utilization in SSA exist, but these efforts are not documented and analysed sufficiently.

Therefore, this paper aims to contribute to the research on ways to produce cleaner products in SSA. This case study of Amelia Agro Africa Ltd., a Ugandan farm, presents the further economic utilization of different non-hazardous and non-infectious waste materials (hereafter industrial waste) by using the models of IS and integrated farming systems (IFS). For analysis, the paper applies schematic modelling of IS fitness conditions for companies, revealing the actors' organizational motivations and financial gains. Data was collected through two field visits in May 2021 and June 2022, which included participant observation and twelve qualitative interviews with existing and potential partners.

The results also indicate that further research on the economic fitness conditions of industrial symbiosis may deliver valuable inputs for policymaking and regulation on enhancing resource efficiency. For instance, landfilling taxes represent the most important cost items for the nine supplier companies analysed in this study. This indicates that policy measures aimed at reducing waste generation and increasing resource use efficiency may become less effective as these taxes increase. Instead, policy should focus on helping companies reduce or avoid disposal and related costs. Understanding the cost structure of waste resale is crucial for considering these alternatives, as explained below. The findings can also assist farmers in discovering alternative methods to boost productivity and provide industrialists with best practice examples to generate additional revenue and save money through waste materials.

Beyond these practical implications, the paper contributes to the literature in three ways. First, the literature covers IS and IFS but barely touches on combining the two with the presentation of such abundant materials utilized in SSA. Thus, this insight into Amelia Agro farm's functioning provides an excellent two-in-one learning opportunity. Second, the paper is one of the first attempts to analyse the economic determinants of IS on the micro level based on primary data. Through this, the role of potential incentives can be better understood, conceptualized, and applied in policymaking. Finally, as most articles focus on the potential benefits to gain *if* these practices were implemented, the paper has a gap-filling character since it examines these practices as *already implemented*.

The paper is structured as follows. The upcoming section is a literature review on IS and IFS in general, and specifically, in SSA. This is followed by the research methodology. The subsequent section presents the results: Amelia Agro Farm's IFS model; IS relationships with its suppliers, the supplier companies' analysis based on a fitness condition equation; and further observations. Finally, lessons learned, limitations, and directions for further research are discussed and followed by brief conclusions.

2. Literature review

Based on Stahel (2016), the circular economy can be summarized in six fields of action: take, make/transform, distribute, use, recover, and *IS*. Industrial symbiosis can be described as a relationship in which one company's waste is used as production input by another company. In other words, IS focuses on closing pre-consumer loops by capturing the residues from one entity as the input for another (Chertow, 2000). Companies participating in this special form of synergy can save on inputs, transportation and landfilling costs, and gain additional revenues from selling waste and by-products (Neves et al., 2019). Henriques et al. (2021) differentiated four levels of IS: internal exchange, external exchange, eco-industrial parks and urban industrial symbiosis. This paper focuses on the former two: internal exchange, which refers to the development of synergies within one certain organization, and external exchange, referring to the exchange of waste among two or more companies.

There is a limited number of studies about industrial symbiosis in SSA. Brent et al. (2008) reported findings on seven cases of eco-industrial parks in South Africa. Oguntoye et al. (2019) reflected on the Gauteng Industrial Symbiosis Programme run in 2014. The Ellen McArthur Foundation (2020) mentioned the case of the Western Cape Industrial Symbiosis Programme as the first African IS programme. Mbuligwe and Kaseva (2006) assessed industrial solid waste management and resource recovery practices in Tanzania. Alfaro and Miller (2013) analysed the potential of integrated material and energy flows in a smallholding farm in Libera, including IS and IFS approaches, similar to this paper. Furthermore, Oliyade (2015) identified sixteen factors that contribute to the success of industrial ecology in SSA. Mauthoor (2017) analysed the potential of IS in three industries (slaughterhouses, edible oil refineries, and scrap metal recycling) in Mauritius. Rweyendela and Mwegoha (2020) explored IS forms in the sugar industry, using the case of the largest sugar factory in Tanzania and involving physical exchanges of bagasse, molasses, filter cake, boiler ash and utility sharing among seven co-located units. Kisha and Onyuka (2018) presented an analysis of the potential greening of special economic zones and industrial parks in Kenya, specifically speaking about the need for the up-take of IS practices, while Jensen (2020) presented cases for the garments sector in "eco-industrial" parks in Ethiopia. Finally, Oni et al. (2022) thoroughly analysed the challenges and prospects of industrial symbiosis in the African continent based on the availability and characteristics of waste materials, some already existing IS networks, and the local regulatory environment.

IFS considers small-holder farms as a system that connects and integrates its different units to increase agricultural productivity (Simmonds, 1985). In brief, it combines two or more fields of agriculture and employs a recycling biological concept while also focusing on low external input utilization. It is most commonly implemented through the utilization of crop waste, animal manure, and fish waste to increase farming productivity and maintain environmentally friendly conditions (Mukhlis et al., 2018). Referring back to the above categorization of IS levels, IFS's approach fits into the internal exchange category. The FAO (2001) also describes integrated systems as an alternative to diversified models with only co-existing but not interconnected livestock and crop cultures. The products or by-products of one component serve as a resource for the other, and this integration helps maximize the use of resources. According to Chan (1985), integrated farming systems can help address food problems in the "Third World" by dealing with rising fuel, industrial feed, and fertilizer prices.

Although the concept of IFS has been embraced and disseminated, research on IFS in SSA is relatively scarce. Dessie (1997) analysed scavenging poultry in IFSs in Ethiopia. Harris (2002) focused on the usage of IFS methods, including manure and cereal residues in the semi-arid Sahel region. Agbonlahor et al. (2003) concluded that a poultry-based integrated food production system could increase soil productivity in Southern Nigeria. Ruddle and Prein (2006) presented an assessment methodology for the impacts of an integrated agriculture-aquaculture system in Ghana. FAO

(2009) reported on enhancing crop-livestock systems in Burkina Faso. Singbo and Lansink (2010) demonstrated the production efficiency increase when applying an IFS approach in rice-vegetable farming in Benin. Obi (2013) presented statistical evidence of small-holder farmers potentially benefiting from IFS in South Africa. Ezeaku et al. (2015) shed light on how cereal-legume-livestock integration can contribute to soil fertility and overall food productivity improvement in the savannah areas of Nigeria. Agosson et al. (2016) described the model of the Songhai farm in Benin as employing integrated farming techniques.

The studies of IS in Sub-Saharan Africa often overlook the economic factors that determine the feasibility of the symbiotic relationship for businesses. However, existing literature widely agrees on the significance of regulations and economic incentives in enabling IS (Boons et al., 2011; Lethoranta et al., 2011; Neves et al., 2019; Lybaek et al., 2020, Bertani et al. 2019; Henriques et al., 2021). In most cases, landfilling taxes, subsidies on logistic or operational costs and material prices are identified as economic factors and incentives. Economic incentives promote cost effectiveness, service efficiency and the generation of revenue. Moving waste up the hierarchy towards minimization, reuse and recycling can be achieved through economic instruments and incentives, provided they are appropriately designed and implemented (Nahman and Godfrey, 2012). Finally, economic incentives create connections between the macro and the micro/meso levels. Thus, understanding the role of certain microeconomic factors could provide inputs for sustainable IS policymaking.

3. Methodology

This paper aims to present and analyse waste materials' utilization in the SSA context. To do so, the research operated with a case study method, since "a case study is best defined as an in-depth study of a single unit (a relatively bounded phenomenon) where the scholar's aim is to elucidate features of a larger class of similar phenomena" (Gerring, 2004, p.341).

Amelia Agro Africa Ltd. is a small-scale organic farm in Jinja, Uganda. They grow several varieties of plants, raise animals (chicken, fish, pigs, cows, goats, rabbits), and produce organic fertilizer (compost) for the local market. The farm uses several waste materials for composting, feeding animals, and plant protection due to a great number of IS relationships both internally and externally. This makes it perfect for a case study to: a) present a variety of waste and by-product materials suitable for further economic utilization in SSA and b) enable the research to examine the economic factors, gains and costs of the farm's IS partners, and thus inform the conceptualization of a local incentive policy. This latter element is even more significant, as the farm's IS clientele represents nearly one-third of the Ugandan manufacturing sector's portfolio[1] (MTIC, 2021, p.5).

Amelia Agro was first visited in May 2021 (Buda, 2022) based on experts' recommendations at the Uganda Cleaner Production Centre and National Planning Authority. This trip was motivated to answer the research question (RQ1) "How can industrial and agricultural waste be utilized in Sub-Saharan Africa?" Therefore, the farm's operation was observed and studied, and the IS and IFS aspects were discussed with the farm's managing director. This also included identifying supplier companies for further company visits and interviews. The description of different material utilization practices, presented below, enables a partial answer to this first research question. Following this initial fieldwork, the waste materials utilized and practices applied through IS by the farm were researched via a literature review.

After, a second research question (RQ2) was formulated: Why is IS worth it for participating companies? This enables capturing the role of economic factors. To theoretically conceptualize this research question, two fitness condition equations based on Boons et al. (2011) and Bertani et al. (2019) were applied to model the positive and negative costs of supplier and buyer companies in IS.

For simplicity, there are two assumptions: 1. suppliers carry out necessary waste treatments and bear related costs, and 2. the transportation of input materials generates costs for the buyers. Thus, economic factors for suppliers and buyers are different, which needs to be considered explicitly.

Hence, the IS fitness condition for a supplier company is as follows:

$$c_{st} + c_p - p_w \leq l + c_{trl} \qquad (1)$$

where
- c_p is the pre-processing and/or handling cost of waste;
- c_{st} is the cost of storing waste;
- p_w is the waste selling price;
- l is landfill tax;
- c_{trl} is the transportation cost to the nearest landfill location.

Therefore, IS fits supplier companies as long as their costs of waste selling are lower than those of landfilling.

For a buyer company, the IS fitness condition can be described as follows:

$$p_w + c_{trw} \leq p_v + c_{trv} \qquad (2)$$

where
- p_w is the waste selling price;
- c_{trw} is the cost of waste transportation;
- p_v is the price of virgin material;
- c_{trv} is the virgin material transportation cost.

So, IS is suitable for buyer companies as long as their costs related to using waste materials are lower than their costs related to using virgin materials.

Following this conceptualization, a second field research was carried out in June 2022, through which data was gathered from the suppliers' side. Nine companies whose waste materials are utilized by the farm were visited and interviewed. This data collection method was chosen against other ones, such as anonymous online surveying, because informants may require guidance and explanation of certain questions, and additional information and further observations can also be gained. These nine informants represented more than two-thirds of the farm's suppliers and were selected based on their availability and willingness to respond. Furthermore, the researcher also visited two other companies as potential future suppliers and one agro-waste distributor company selling materials to the farm. In accordance with the IS fitness condition (1) for suppliers, the semi-structured interviews focused on the following aspects:

1. supplier's primary motivation to participate in the IS relationship;
2. landfilling costs saved;
3. transportation costs to landfill saved;
4. storage costs realized;
5. handling or pre-processing costs realized;
6. whether Amelia Agro pays for the received material;
7. whether Amelia Agro pays for the transportation of waste received;
8. the value of these cost items relative to each other.

In line with the above-mentioned logic, the paper applies the model of IS and equations (1) and (2) as its theoretical framework. The results presented in the following section should be seen as snapshots from the two field visits in May 2021 and June 2022. Amelia Agro is continuously experimenting with the utilization of new industrial materials to broaden its supplier portfolio, improve economies of scale, and elaborate best practices. Based on the low sample number, these results are not representative and not statistically significant, yet they serve to deepen the understanding of the research topic.

4. Research Results

This section first presents the in-house circularity of materials on the farm, reflecting on IFS. This is followed by the farm's IS relationships with the nine suppliers. The gains and motivation of the supplier companies are then analysed, and further research observations are presented.

4.1. Integrated farming model – within-unit circularity of materials

The farm has a circular model of materials, demonstrating a perfect example of IFS. Everything, including animal manure, weeds, or other plant remnants, is utilized for feeding or composting. The manure from pigs, cows, goats, and rabbits is used as an input for vermicompost and windrow compost. Urine is an input for liquid fertilizer. Cow manure is also used to feed black soldier flies. Chickens are located right above a fishpond; thus, their manure drops directly into the water, which serves as feed for tilapia fish and water hyacinth. This practice is also mentioned by the FAO (2001). The maggots of black solder flies serve as protein-rich fodder for the pigs and fish. The water hyacinth is fed to pigs and chickens and provides input for the windrow compost and liquid fertilizer. Plant and vegetable off-cuts and weeds are fed to the animals on the farm (pigs, cows, goats, rabbits, chicken and fish), while some plants are specifically grown as fodder, such as moringa, calliandra, gliricidia, mulberry and duckweed. The three types of organic fertilizer (vermicompost, windrow compost, liquid fertilizer) serve to increase soil fertility. The model is visually presented in Figure 1.

This in-house circularity of materials enables the farm to realize cost reductions for the necessary production input materials and improve soil fertility. Furthermore, CO2 emissions from open-air waste decomposition are minimized, as animal and plant-based materials are kept in the production circle. However, maintaining this continuous circularity is very labour-intensive and thus generates additional labour cost burdens for the farm. In one sense, this represents a meaningful social benefit via the jobs generated, but it also raises serious questions regarding economic sustainability and economies of scale.

4.2. Industrial symbiosis

The following section presents nine suppliers' by-products that the farm utilizes as waste materials. It also includes information about how each material is used on the farm and additional research findings about similar applications. Additionally, Figure 2 illustrates the primary destination of the farm's waste materials.

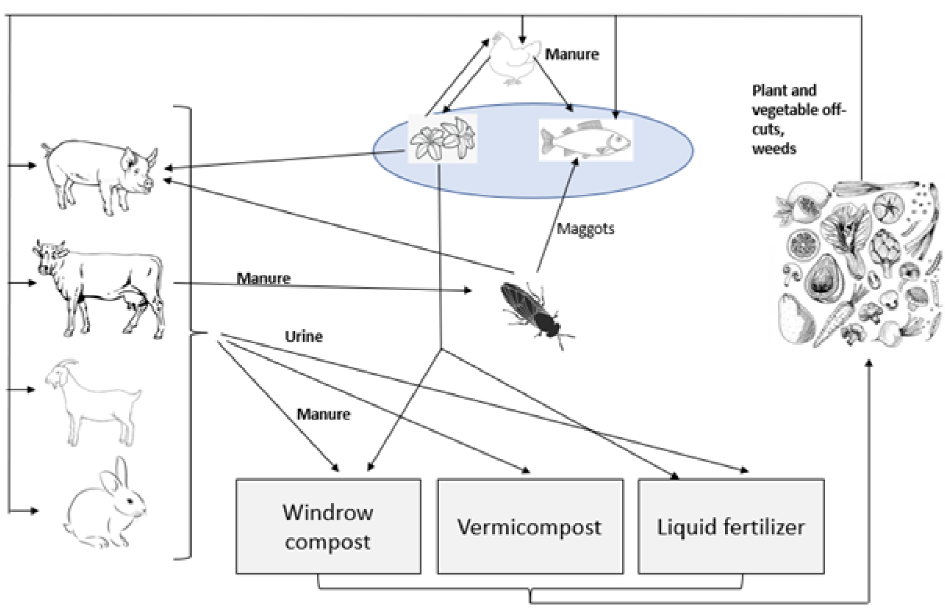

Figure 1. Within-unit circularity of materials at Amelia Agro farm. Source: author's construction

OBN Produce and Supply Ltd. is a rice mill in Jinja that sells rice husk to the farm for use as chicken bedding, fodder, and compost input. Otherwise, the company would simply "dump or burn" this material, so its further utilization clearly generates environmental benefits. Zhao et al. (2022), for example, demonstrate how rice husk can be an important component of organic fertilizer mixtures.

Bagasse is received from GM Sugar Ltd. and used as mulch. It is applied to the soil surface to maintain the soil moisture, improve the soil's fertility and health, and reduce weed growth. Another purpose of bagasse is to supply the pigs with protein-enriched feed (Pandey et al., 2000). GM Sugar also uses this waste in-house. Seventy percent of the bagasse goes for power generation for its factory.

The Jinja City Abattoir, a slaughterhouse, supplies the farm with blood, intestines, and flesh off-cuts. Other flesh residues are also received from a fish producer, Nyanza Perch Ltd., and a tannery, Mekah Leather Ltd. Composting of meat/fish processing waste such as dung from the lairage, ruminal and intestinal contents, blood, meat trimmings, floor sweepings, hair, feathers, hide trimmings, as reported by Kharat (2018), produces a very good quality bio-manure which may be utilized as fertilizer. Furthermore, slaughterhouse waste has been reported to be a significant source of proteins and fats that are convenient raw materials for processing proteinaceous animal feeds (Okanović et al., 2009). Regarding the utilization of fish waste as compost input, Kusuma et al. (2019) show that the level of organic carbon, nitrogen, phosphorus and potassium makes fish waste-based compost applicable as organic fertilizer. Similarly, Ahuja et al. (2020) also reveal that fish waste-based fertilizers are rich sources of nitrogen and phosphorus for plants and positively affect soil quality by improving soil microbial activity and soil structure and stimulating root growth.

The by-product of a local paper company, East African Packaging Solutions Ltd., carbon-rich boiler ash is another valuable source for improving soil fertility; thus, it is used by the farm as a windrow compost input, mixed with other organic materials. Focusing on forest-lands in the USA, Vance (2000) concludes that paper mill boiler ash can be beneficial for plant (tree) productivity, as it is mainly comprised of oxides and carbonates of potassium and calcium but also contains significant amounts of phosphorus, magnesium, and some other micronutrients. As a soil amendment, one of the most essential characteristics of ash is its effect in raising the soil's pH value, as demonstrated by its effective substitution for agricultural lime. Moreover, boiler ash generally has low concentrations of heavy metals, organic compounds, and other constituents of concern, and it is environmentally benign when used in reasonable quantities. This is in line with many other studies (Vance, 1996; Wang et al., 2006; Brotodjojo and Arbiwati, 2016) concluding that boiler ash can be applied as an agricultural liming material, soil conditioner, fertilizer or even plant resistance enhancer against insect pests. Besides boiler ash, other paper production by-products, such as sludge, can also be applied as organic fertilizer (Fahim et al., 2018).

Spent grain, spent yeast, and malt dust from Nile Breweries are fed to the pigs and fish and then used as compost components. Assandri et al. (2020) conclude that brewers' spent grain is not suitable for direct composting, therefore, it should be mixed with livestock manure, as it is done in practice at the farm. Another potential utilization form is to feed these residues to animals (Ajila et al., 2012; Karlovic et al., 2020). The brewing process is one of the most waste-producing ones in proportion to the end product and includes wastewater, spent grains, spent yeast, spent hops, and germs (Amoriello and Ciccoritti, 2021).

Distillate spent wash from Buwembe Brewers and Distillers Ltd. is also used as an input to liquid fertilizer. Distillery effluents represent a significant agro-potentiality by positively affecting the moisture and mineral content of the treated soil (Chopra et al., 2013), and thus, if used in lower concentration, can positively affect seed germination and yields of several plant species, such as wheat, pea, okra (Pandey et al., 2007), rice (Arora et al., 1992), maize (Ramana et al., 2002), and Chinese cabbage (Kumari et al., 2016).

Bidco Uganda Ltd. produces cooking oil from palm. As a by-product of palm oil extraction, between 200 and 400 tonnes of kernel expeller are produced every month. This material is utilized by the farm as animal feed input, as it is a quality stock feed containing high levels of crude protein and medium energy levels, thus safe to feed as a supplement for most classes of livestock (van Wyngaard et al., 2015; Thompson-Morrison et al., 2022).

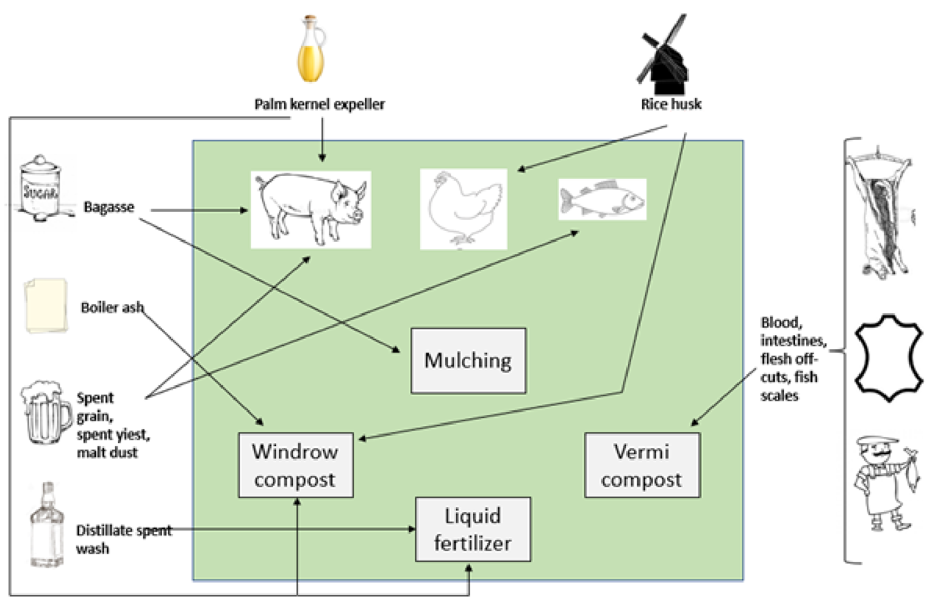

Figure 2. Waste materials received by Amelai Agro. Source: author's construction

4.3. Suppliers analysis

This section briefly presents the research results regarding the main motivating factors and the cost items based on equation *(1)* for the nine supplier companies presented above. Table 1 summarizes the results.

Five of the nine companies interviewed mentioned the generation of additional revenue as the primary motivation. The other four highlighted the existing or potential saving of landfill and waste management costs as their most important incentive, including the avoidance of special taxes.

Only three companies stated that they are already saving *landfilling costs* with the ongoing relationship, while the other six did not, due to different reasons such as the small quantity taken by the farm relative to the total quantity of waste or irrelevant landfilling cost in case of no purchase, such as free usage of the landfill, simple dumping, releasing to natural water bodies or giving-away for free to company workers.

Five companies realized savings on *transportation costs to the landfill*; this aspect was irrelevant for four other firms. The number of companies realizing savings in landfilling costs and those realizing savings in transportation costs do not overlap. This is because some companies still have to transport much of their waste or by-products to the landfill, or even if they do not have to pay for the landfill, they still have to bear the transportation costs.

The interview questionnaire was formulated to probe the potential savings in *storage costs* if the farm (or any other customer) takes the provided materials. Of the nine companies, only three mentioned savings of storage costs (in one case, espe-

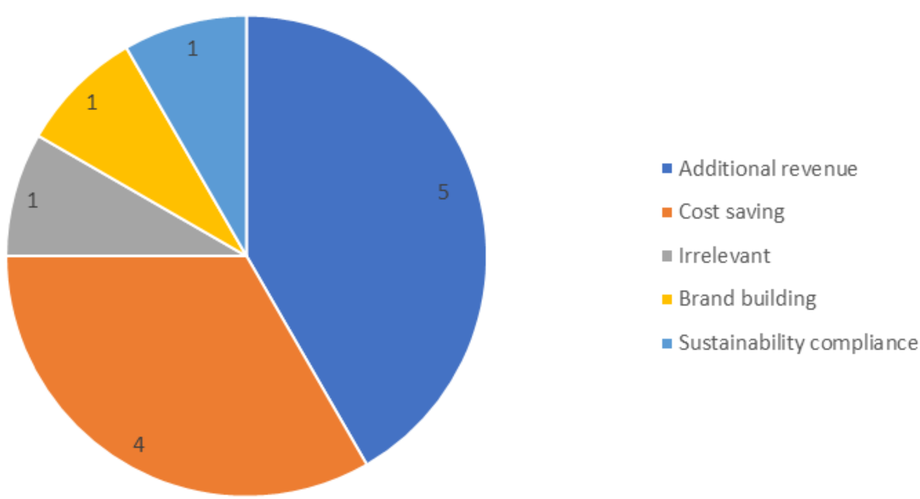

Figure 3. Motivations in waste/by-product supply of the nine suppliers of Amelia Agro. Source: author's construction

cially high due to obligations around special storage conditions). For six companies, this was irrelevant.

Handling and pre-processing costs are realized as positive cost items for the companies and refer to additional treatments before giving away the waste or sending it to the landfill. Four companies mentioned these costs as relevant, and the other five do not face such additional costs. From the IS point of view, these costs were important for analysis since they can mean additional costs in case a special client needs them or potential savings if these treatments are not necessary for the partner. However, none of these two cases occurred in the research.

The farm *pays for the waste materials* to six of the nine companies and, in each case, pays for waste transportation. This indicates that only a minority of the companies are motivated to "simply get rid of" the waste materials. Even if they let the farm take them for free, they do not want to incur additional costs (for transportation).

As a last point in the data collection process, interviewees were asked to estimate a ranking among the cost items of the supplier fitness condition equation (*1*) to find a ***relative relationship among these cost items***. Unfortunately, not every respondent was able to give an estimation to this question, and these cost items differ significantly depending on the exact activity and technology. In the sample of these nine companies, it seems that the waste selling price (p_w), the only negative cost (i.e. revenue), is by far the least important item for the supplier companies in this equation. It is followed by the cost of transportation to the landfill (c_{trl}) and storage costs (c_{st}). The costliest items are pre-processing or handling costs (c_p) and the payment for landfilling (I). Thus, in this sample of nine companies, the relative relationship can be expressed as follows:

$$(p_w) < (c_{trl}) < (c_{st}) < (c_p) < (I)$$

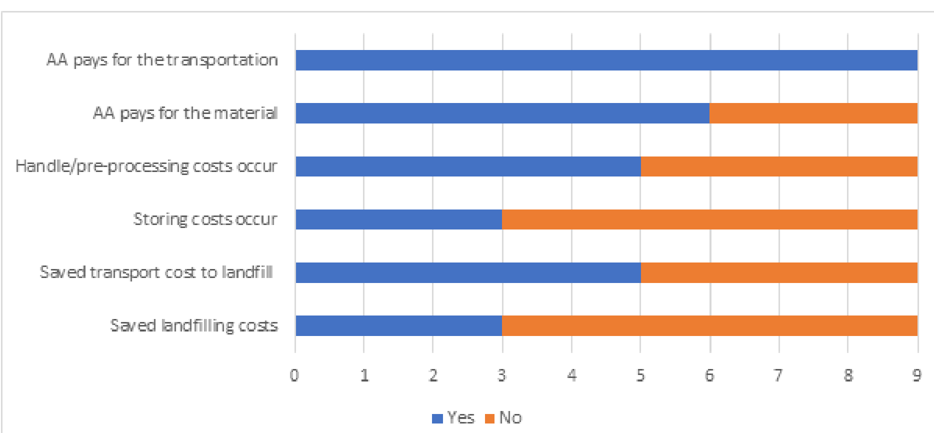

Figure 4. Occurrence of cost items by the nine suppliers of Amelia Agro.
Source: author's construction

4.4. Further observations

This final subsection shares additional information gathered during the research, which may contribute to the broader understanding of waste utilization in SSA. These insights are informed by visits to further companies that are not included in the supplier analysis above.

First, the sugar industry has great potential and, in many cases, already has an applied practice of in-house utilization of waste and by-products. As mentioned above, GM Sugar uses around 70% of the bagasse for power generation. Other big sugar companies, such as SCOUL (Sugar Corporation of Uganda Limited, visited as a potential new partner for the farm), reported similar practices. Besides power generation, SCOUL also makes use of molasses by operating a distillery, and sells CO_2, another by-product generated in the process.

Second, Uganda Tea Corporation Ltd. in Kasaku Estate was also visited as a potential partner for the farm. Several by-products of tea processing, such as micro-fined tea dust, winnowings, floor sweepings and tea seeds, can also be utilized as valuable inputs for composting and feeding (Guil-Guerrero et al., 2016).

Third, in many cases, waste and by-products are re-distributed by middlemen to the farm and other customers, such as spent grain from Nile Breweries or other suppliers not included in the analysis above. These intermediaries include Jose AF, a dealer of spent grains and a company contracted by Eskom, the operator of the Jinja Damm, to clean off water hyacinth from the water surface and solve its disposal by selling it to farmers as pig fodder. The role of intermediary companies in IS may form the subject of consideration to modify the fitness condition equations above, but that is beyond the scope of this paper.

Fourth, one can detect some “low-hanging fruits” for regulation to facilitate industrial symbiosis. Certain materials, such as boiler ash or distillate spent wash, are produced in huge quantities, that potentially add value to compost production and organic fertilization. Their storage, handling and disposal can be extremely costly for the producer and harmful to the environment. Sometimes, the realized costs have already incentivized companies to look for waste-selling opportunities. In contrast, primarily due to the poor enforcement of environmental laws, the cost of disposal is still less than the cost of selling the waste, which holds companies back from being interested in further utilization of waste. This implies that supporting waste material utilization in production might require subsidies on the cost of waste selling, as it is the least important cost item for most companies and/or for related storage, handling, or pre-processing activities.

5. Discussion, limitations and further research

This paper aimed to find answers to the utilization opportunities of waste and the costs and benefits of companies in IS relationships. The former topic was easier to identify because one can describe the processes based on interviews and company visits. For the latter part, the paper modelled negative and positive cost items in equations *(1)* and *(2)*. Even though the model seems appropriate, gathering data for it was problematic. Costs and income items are very sensitive; companies generally do not like to share this information. Thus, one faces a serious limitation when applying this model: data for a quantitative model needed to be gathered using qualitative methods. Hence, to address this problem, the questionnaire contained yes-or-no questions regarding certain cost items and a ranking to see the extent of these items relative to each other. This enabled testing the fitness condition equation. However, the issue can still be the subject of further research using different data collection methods.

Another important limitation point is the question of external validity due to the small sample size. The paper contains much information regarding the kinds of waste or by-products and how they can be utilized. It may deliver valuable ideas and practices for other companies in Africa. However, it is still a question to what extent the research findings for the cost items can represent the broader phenomenon of waste material utilization, as these factors are strongly dependent on technology, industry, and regulation. This calls for further research, which may include other industries and activities, and gathering more data for testing and developing the equations.

Furthermore, this research did not focus directly on the role of regulation and policy-making. Rather, it focused on the nuclear elements of IS. Nevertheless, the findings may inspire policy-making on how to incentivise economic actors to utilize or sell waste and by-products. One can already see a pattern in the above results. The most important cost item was the landfilling tax, while the lowest was the selling price (revenue). The three other cost items (landfill transportation, storage, handling and/or pre-processing) differ greatly according to the given technologies and materials. This means that a standardized policy intervention related to these latter three cost items may be difficult; rather, a case-by-case method would be preferable if such institutional capacities are available.

Thus, in line with the IS literature, policy-interventions can most easily focus on the landfilling taxes and waste selling prices. For instance, increased taxes can motivate companies to avoid waste disposal and look for ways to sell their waste materials. However, this approach may result in failure and illegal waste disposal due to the following reasons. In many cases, only some part of the waste materials is sold as a production input, therefore, the increased tax paid for the not-sold amount is an additional burden on companies. Furthermore, if supplier companies need to increase the amount of waste for sales, their necessary storage and handling/pre-processing costs may also increase or even exceed the amount of tax paid, thus breaking the equation *(1).* Additionally, the avoidance of illegal disposal and the enforcement of higher tax payments require strengthened institutional capacities to control and effectively punish, which can lead to additional regulatory costs higher than the overall benefits. This aspect was not included in the above research, but one may assume that the local authorities in Uganda and in the region have limited resources to operate such an effective system. An increase in the selling price of waste could strengthen the IS equations. This could be achieved through two methods: subsidizing the price of waste materials or imposing taxes on virgin raw materials. The former option seems preferable as it directly encourages the use and reuse of waste materials, reducing their disposal. On the other hand, increased taxes on virgin raw materials could have a negative impact on industries that rely on these materials and do not have access to sufficient or regular amounts of waste materials.

Finally, this research applied the approach and tools of economics and the broader social sciences. Some insights from the natural sciences were included, but the examination of actual natural effects, such as decomposition, addition to nutritional value, and technological barriers, just to mention a few, will need interdisciplinary research.

6. Conclusion

Sub-Saharan Africa faces serious challenges in agricultural productivity and potential future industrial waste generation. To address these combined issues, this paper aimed to answer two research questions through the case study of Amelia Agro Africa Ltd. in Uganda: (RQ1) *"How can industrial and agricultural waste be utilized in Sub-Saharan Africa?"* and (RQ2) *"Why is industrial symbiosis worth it for participating companies?"* Data was collected via two research trips in 2021 and 2022 and through desk research.

To answer the first question, the research focused on the models of IFS and IS. Regarding IFS, the within-unit circularity of organic materials from seven animal species and several plant species was presented, as these elements are used as inputs for three different types of compost (windrow, vermin, liquid) and animal feed. For IS, the utilization of animal feed, compost input or organic pesticides of industrial waste or by-product materials coming from nine companies was analysed (such as rice husk, bagasse, animal blood, intestines, flesh off-cuts, fish remainings, boiler ash, brewery by-products, distillate spent wash and palm kernel expeller).

Regarding the second research question, the research applied an IS fitness condition equation to detect factors influencing the positive and negative costs of the companies supplying waste materials to the farm. These are landfilling costs, transportation costs to the landfill, storage costs, handling and pre-processing costs, waste selling price and transportation to the buyer. In line with IS literature, the main motivations of these supplier companies were additional revenue generation and savings on landfilling costs. On average, the most significant cost items were landfilling, followed by handling and pre-processing costs, while storage and transportation to landfills were less important. The waste selling price was minimal relative to the other cost items. One common point among the nine companies was that the farm solves and pays for the transportation of the given material in each case.

This paper is part of a larger research project and aims to inspire further scholarly work on the economic use of waste or by-product materials in Sub-Saharan Africa. To gain a deeper understanding of the potential facilitating or hindering factors of industrial symbiosis, we need many more similar case studies from various African countries, preferably in an interdisciplinary approach. Ideally, these studies should include larger sample sizes to support the external validity of results and provide input for local policymaking and regulation.

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Note

1 According to the Ugandan Green Manufacturing Strategy, the local manufacturing sector comprises mainly manufacture of food products, beverages, tobacco products, textiles and clothing apparel, leather and eather products, wood and wood products, paper and paper products, chemicals and chemical products, pharmaceuticals, medicinal chemicals and botanical products, rubber and plastics products, basic metals and fabricated metal products, cement and bricks. The presented IS relationships in this paper cover nearly one-third of this portfolio.

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