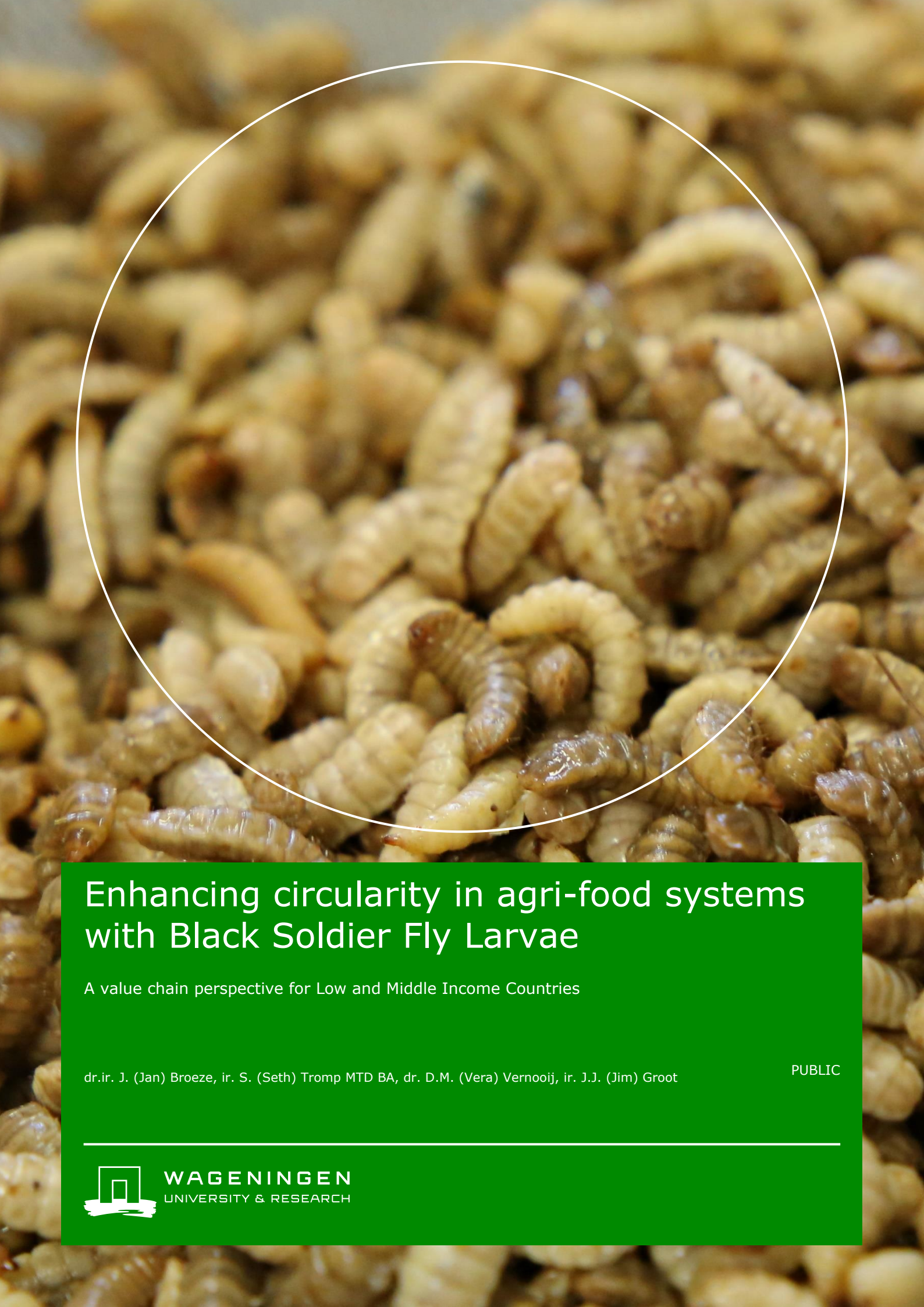

Enhancing circularity in agri-food systems with Black Soldier Fly Larvae

A value chain perspective for Low and Middle Income Countries

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Contents

Summary

Food losses (FL) and food waste (FW) are considered resources for generating more value in the food system via diverse valorisation pathways. Insects, specifically the larvae of Black Soldier Flies (BSF) (Black Soldier Fly Larvae: BSFL) are considered promising for sustainable food production via valorising FL/FW into human food and animal feed[1]. In this report we identify important factors for building profitable BSFL supply chains in Low and Middle Income Countries (LMIC), and explore the potential for valorising FL/FW in Kenya to proteins for contributing to food security. It asks: Which factors are important for establishing profitable BSFL value chains in LMIC? (Chapter 3), and what is the potential of BSFL to valorise FL/FW into proteins in Kenya? (Chapter 4). The first question was answered via reviewing eight peer reviewed publications, and the second via calculations based on public data.

Chapter 2 introduces the BSFL life cycle, production cycle, and typical processing steps from collection of food waste to final insect biomass (Figure S.1).

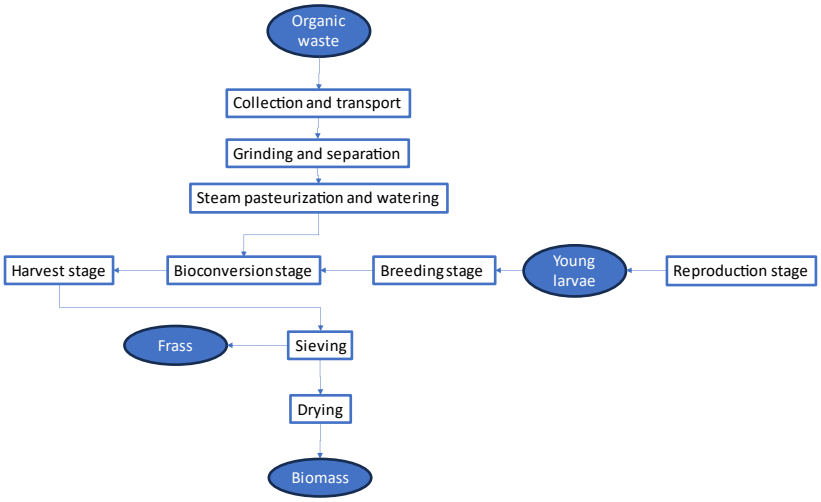

Figure S.1 Processing steps from collection of food waste to final insect biomass

In Chapter 3, the case studies from the literature show key factors relevant for economic feasibility of BSFL farming, which include labour costs, substrate costs including transport, costs of starter eggs/young larvae, energy costs, the price of the final products, and the conversion efficiency of FL/FW into feed and food. BSFL farming in LMIC can be promising because of favourable climatic conditions compared to colder climates, which reduces the need for energy, but overall production costs can be high, just like the capital requirements. From a logistical perspective, production closer to peri-urban and urban areas compared to rural areas might be beneficial for creating economies of scale, access to the FL/FW, and available infrastructure. However, animal production and animal feed markets are predominant in rural areas. Capital requirements for BSFL farming are significant, but typically lower than other organic waste valorisation methods. Various motivations/benefits as well as hurdles are summarised for three production scales: small scale farming, regional farming, and large-scale farming.

In Chapter 4 a quantitative analysis is presented based on estimated volumes of food products that are currently managed as waste (thus, that have no functional use as food, feed or added-value non-food use in the current system) in Kenya. It was found that theoretically from selected wasted products, 27.4 kton BSFL proteins can be produced, which fulfils around 2% of the national human protein intake. If the BSFL are fed to layer hens, a maximum 0.6% extra human proteins can be produced in eggs. These percentages can be considered relatively low, but the amounts can be considered significant. Overall, FL/FW valorisation using BSFL in LMIC has potential, but relevant logistical, market, and cost-effectiveness considerations should be regionally explored prior upon initiation, for diverse production scales.

[1] see e.g. https://business.wwf.nl/nl/ons-werk/groen-financieren/bankable-nature-solutions/Dutch-Fund-for-Climate-and-Development/chanzi and https://www.chanzi.co/.

1 Introduction

The potential of Black Soldier Fly Larvae (BSFL) in circular agri-food systems is increasingly appreciated and understood (Liu et al., 2022). There is particularly great emphasis on BSFL rearing opportunities from technical perspectives, mainly due to reasons related to public health and hazard risks as explained below. This report aims to explore the potential of BSFL in circular agri-food systems from a value chain and logistics perspective for Low and Middle Income Countries (LMIC). In East Africa various organisations and communities are engaging with BSFL. We therefore ask: Which factors are important for establishing profitable BSFL value chains in LMIC? (Chapter 3), and what is the potential of BSFL to valorise FL/FW into proteins for food and feed in Kenya? (Chapter 4). The first question was answered via reviewing eight peer reviewed publications, and the second via calculations based on public data.

In food loss and waste accounting, a distinction is made between food losses[2] (FL) and food waste[3] (FW) because of intrinsic difference of characteristics and possible uses. Significant quantities of FL occur in LMIC like Kenya, especially in agricultural production and harvesting, storage, transport and/or processing. Reasons for deriving products from food supply chains include harvest failures, overproduction (e.g. during seasonal supply peaks), quality issues and safety issues (e.g. mycotoxins) (Affognon et al., 2015; Makkar, 2017). Established uses of such streams include channelling to lower-end food markets including donation, processing to food ingredients and application as animal feed. Next to such 'productive' uses, substantial volumes are lost (e.g. eaten by rodents) or removed as waste (e.g. dumped, landfilled, composted or anaerobic digested). FAO (2019) estimates the quantity of food lost to 'non-productive' destinations from post-harvest to distribution in 2016 in Sub-Saharan Africa (SSA) around 16% of the total harvested volume.

In LMIC the quantities of FW in amongst others retail, food service and households, are considerably lower than FL, but still very substantial (Mmereki et al., 2024). Because – at least in urban areas – these stages of the food supply chain are typically disconnected from agricultural production, a 'productive' use as animal feed is often not possible. Most FW is landfilled or dumped along roadsides and in water bodies (Kathambi et al., 2022). These destinations induce large environmental impact (like greenhouse gas emissions and pollution) and result in loss of valuable resources.

Most initiatives aimed at reducing inefficiencies in the food system due to FL and FW focus on preventing/minimizing the volumes of FL and FW (Totobesola et al., 2022). However, opportunities for preventing FL and FW are often limited, because of the high level of informality of value chains and limited possibilities to adapt agricultural production to market demands, for example because of seasonal climate and unpredictability of weather and other external influences (Mmereki et al., 2024). Instead, alternative waste management, or rather, options for creating additional value, should be explored (Okuthe, 2024).

Waste management involves the collection and treatment of the wasted products that have no direct use. Various reasons contribute to limited FL and FW management in LMIC, including insufficient infrastructure, institutional weaknesses, and limited allocation of budgets (Mmereki et al., 2024). 'Cheap' options for waste 'management' are most common, namely dumping and landfilling. However, associated environmental sustainability impacts (including concerns with respect to greenhouse gas emissions, unsafety, trouble of rodents, odours, etc.) urge LMIC municipalities to consider urban FW strategies as key action (Pedrotti et al., 2023). In this setting, the chance of success of alternative FL and FW management may depend on their financial feasibility. Understanding the practical potential of circular valorisation may motivate the development.

[2] Food losses are defined as food that gets spilled, spoilt or otherwise lost, or incurs reduction of quality and value during its process in the food supply chain before it reaches its final product stage. Food losses typically take place at production, post-harvest, processing, and distribution stages in the food supply chain (UNEP, 2021).

[3] Food waste is defined as food that completes the food supply chain up to a final product, of good quality and fit for consumption, but still does not get consumed because it is discarded, whether or not after it is left to spoil or expire. Food waste typically (but not exclusively) takes place at retail and consumption stages in the food supply chain. Overbuying, poor planning, and confusion over labels and safety contribute to food waste at stores and in homes (UNEP, 2021).

A circular economy concept aims to overcome the linear pattern of "take-make-dispose" by adopting circular strategies of "closing the loop." It promotes sustainable and resource-efficient policies and actions for long-term socio-economic, public health, and environmental benefits. For FL and FW, although part of the streams may be unfit for keeping them in the food system (for reasons of safety, e.g. presence of mycotoxins), large volumes are considered suitable (considering that levels of heavy metals, mycotoxins and pesticides should be low in food products), as shown by for example Das et al. (2018) for vegetable waste streams from markets in sub-urban areas around Dhaka.

Guidelines for circular added-value generation from FL and FW streams are provided by the principles of the food waste hierarchy. Selection options higher on the reversed pyramid (Figure 1) are considered to be higher added-value to a product previously regarded as waste.

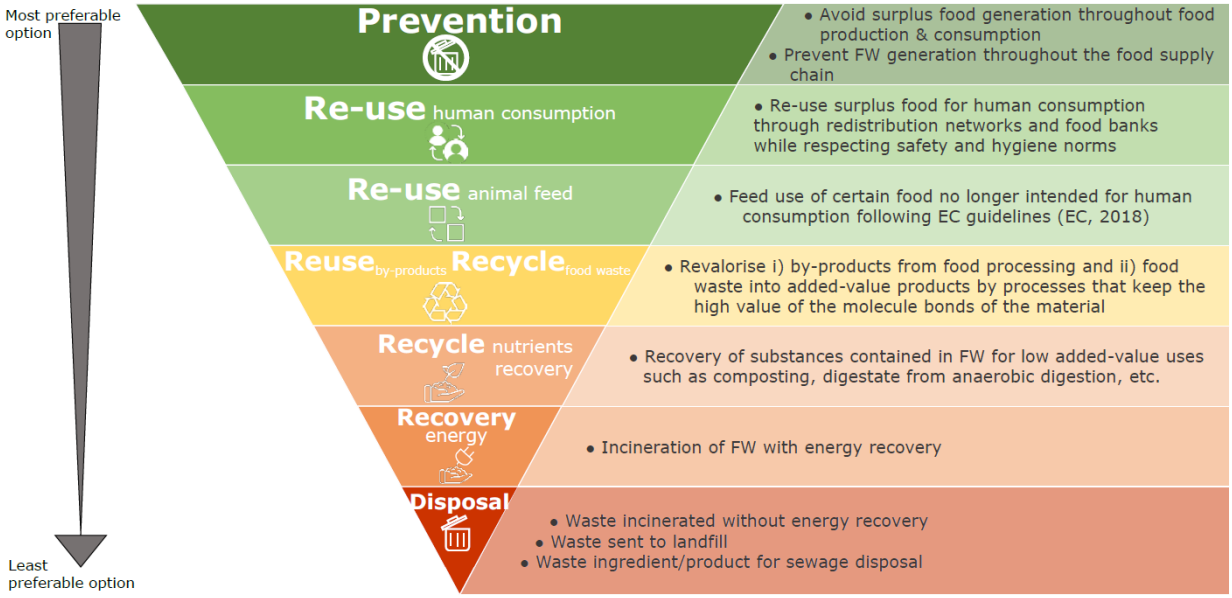

Figure 1 Hierarchy for prioritisation of food surplus, by-products and food waste (FW) management strategies (Sánchez López, et al., 2020).

Substantial fractions of (adequately quality-managed) FL streams are used for the highest possible value below food use (Figure 1): use for feed. In many parts of the world the use of FL/FW streams containing animal-derived materials is strongly regulated, constraining high-value applications of such streams because of possibilities of transmitting diseases like foot-and mouth disease, African swine fever and Transmissible spongiform encephalopathies. However, in diverse countries, including South Korea and Japan, even FW streams that include animal-derived products are 'recycled' as animal feed. In these countries, the practices for food waste collection, transport, storage and treatment are strongly regulated in order to safeguard the safety (Zu Ermgassen et al., 2016).

In situations with less well-managed safety, application as animal feed is considered riskier. In the search for increasing resource efficiency of food production and supply, FL and FW valorisation via insects is considered a promising option for increasing protein supply. One of the most relevant insect species is Black Solder Fly (BSFL), because:

- their larvae can grow on diverse food streams, and consequently food waste and other streams derived from food chains,
- the larvae efficiently accumulate proteins and fat,
- frass, the residue of larvae production, is considered a high-quality fertilizer,
- the pathway upgrades the waste stream to a valuable circular resource.

In High Income Countries (HIC), diverse parties have started insect production at large scale. Strict rules with respect to feed (e.g. in the European Union comparably strict for livestock feed) hinder the use of food waste streams in those production systems. Although insects may form an extra barrier for transmitting pathogens, using former foodstuffs containing meat or fish as feed for insects is prohibited in the EU because of the threat of this transmission (Lähteenmäki-Uutela et al., 2021). Consequently, in the current situation

insects do not substantially contribute to additional food supply there; essentially they serve some small added-value markets (mainly feed for fish and specific animal categories).

In LMIC, where the food security challenge is more critical and generally legislation is less strict (Lähteenmäki-Uutela et al., 2021), insects are considered more promising on shorter notice. Insects grown on FL/FW/residue streams that are not suitable for direct feeding to livestock can be valuable resource for food or feed. Yet, it must be taken seriously that producing insects on food waste streams for food or feed may induce substantial microbial and chemical safety hazards (Surendra et al, 2020; Vandeweyer et al, 2020, Van der Fels-Klerx et al, 2021); adequate selection and management of FL/FW streams and postprocessing of the BSFL is critical.

In this report the analysis of a cost-effective logistic design (Chapter 3) is combined with quantitative estimates of potential contribution to food security through BSFL reared on FL/FW (Chapter 4). Chapter 2 introduces the BSFL life cycle, production cycle, and typical processing steps from collection of food waste to final insect biomass.

2 Life cycle, production cycle and processing steps of BSFL

The development of a system for producing BSFL based on FL and FW involves an integrated system approach: new supply and value chains must be designed, existing chains adjusted, and integrated in the food system. Key elements of the BSFL chains include the collection of FL/FW streams; BSFL production; processing of the larvae, and trade (for food or feed). This chapter elaborates the BSFL life cycle, the similar production cycle of BSFL explaining when the BSFL is ready for processing, and the processing steps from collection of food waste to final insect biomass.

The life cycle of the BSFL is illustrated in Figure 2. This involves the harvesting of eggs to grow into larvae. Following the prepupal and pupal stage, the larvae transforms into an adult fly, which then can lay eggs again.

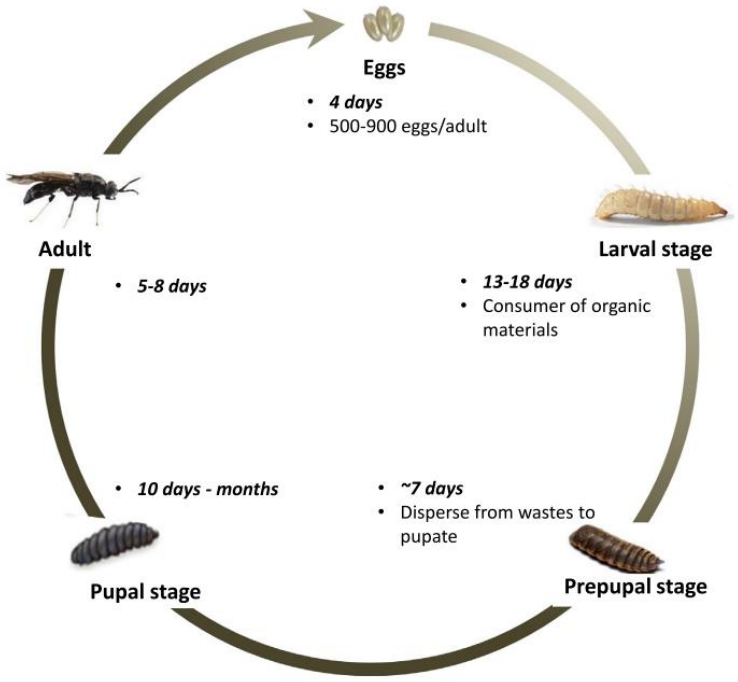

Fig. 1. A schematic of life cycle of the BSF.

Figure 2 A schematic of life cycle of the BSFL (Surendra et al., 2020).

A similar Figure 3 describes the production cycle of BSFL. Under appropriate climatic conditions, simple technology and primitive infrastructure are sufficient to grow BSFL (Liu et al., 2022). After hatching the eggs, the neonate larvae are nursed to the required age to introduce them into the process of processing organic waste. The BSFL feed on organic materials and produce frass, which is the main by-product of insect farming and consists of undigested substrate wastes, excretions, shed larval skins and dead insects. It is promoted as alternative organic fertilizer with positive effects on soil and plant health. Adult and well-fed larvae can then serve as a source of protein raw materials.

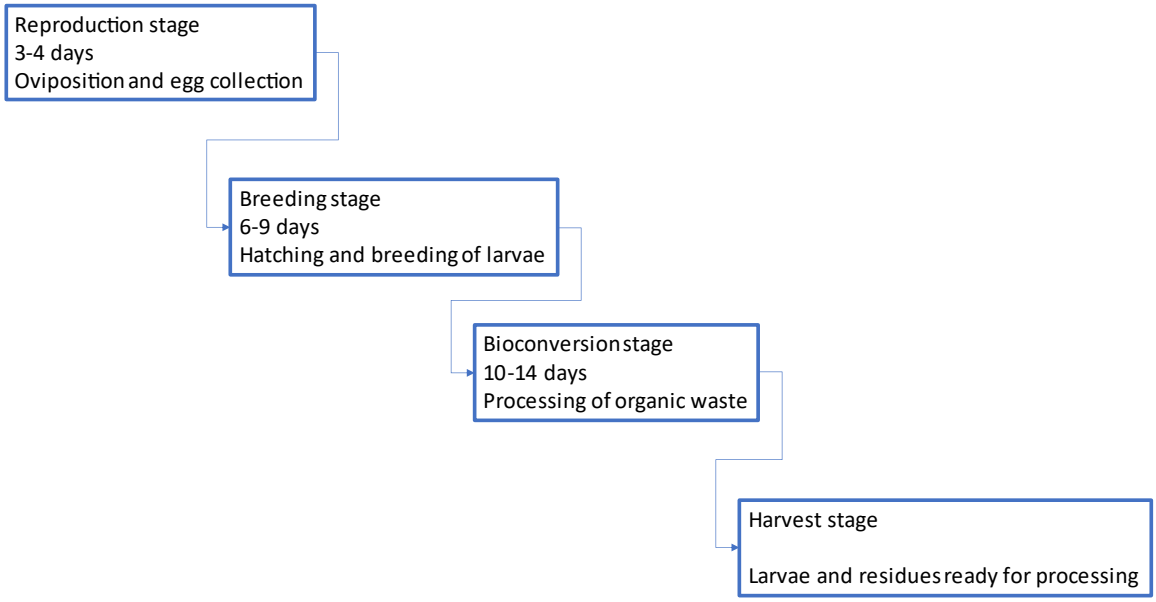

Figure 3 Production cycle of BSFL (based on Liu et al., 2022).

Pleissner and Smetana (2020) have described the typical processing steps from collection of food waste to final insect biomass. We have combined this description with the production-cycle step from Figure 3 to obtain Figure 4. In **Fout! Verwijzingsbron niet gevonden.** the production steps from Figure 3 are presented from right to left. The bioconversion stage is where the larvae meet the organic waste.

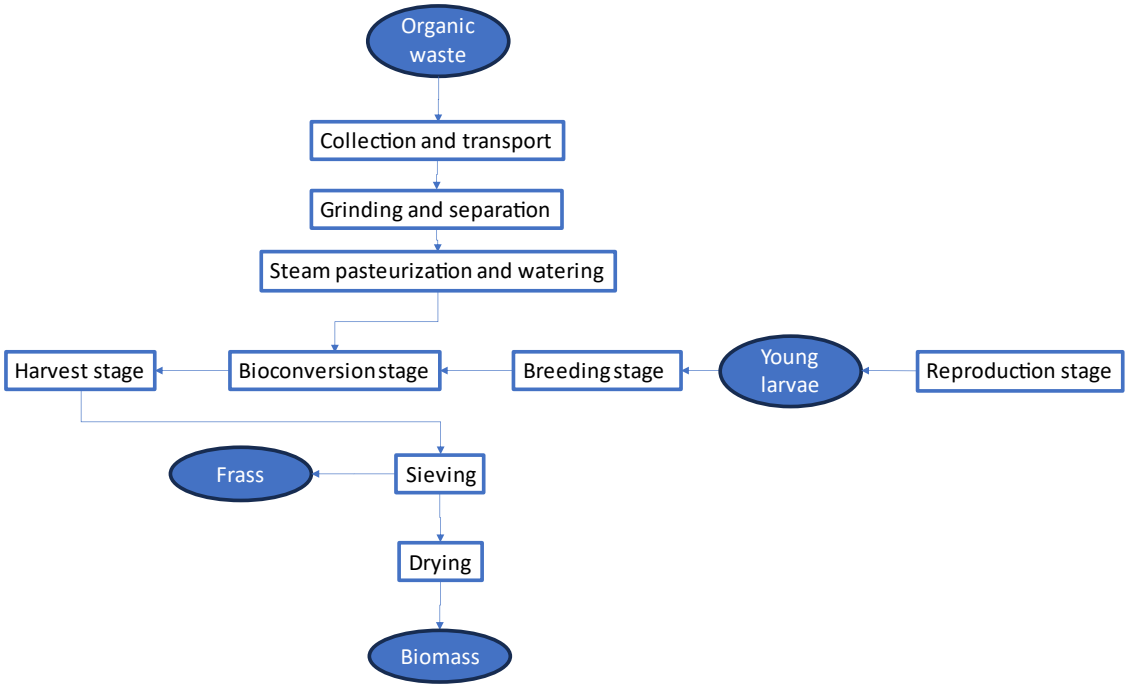

Figure 4 Processing steps from collection of food waste to final insect biomass.

3 Synthesis of case studies on the economic feasibility of BSFL farming

A literature search was performed to investigate which factors are decisive in the economic feasibility of BSFL farming. Due to the limited availability of studies emphasizing economic feasibility in LMIC, HIC cases were included[4]. Eight articles were studied in-depth.

Table 1 summarises the main findings from the literature, and contains the main factors determining the economic profitability of BSFL production. Profitability of BSFL farming largely depends on substrate costs, labour costs, the location of the operation, production scale, energy costs, and the intended use of final products (value-added products including fuel, feed and fertilizer). In some cases the young larvae are purchased, which makes these costs also a factor in determining the economic profitability of BSFL production. The individual articles contain more detailed relevant findings, and these are summarised below Table 1.

Table 1 Summary of most important (i.e. mentioned by at least two publications) factors determining the economic profitability of BSFL production on waste/manure.

	Labour costs	**Substrate costs, incl. transport**	**Conversion efficiency (e.g. type of substrate)**	**Price of final products**	**Production scale**	**Energy costs**	**Costs of young larvae**
Mutuku et al. (2022)	**x**	**x**			**x**		
Munthali et al. (2023)					**x**		
Roffeis et al. (2018)	**x**	**x**	**x**	**x**	**x**	**x**	
Liu et al. (2022)		**x**	**x**	**x**	**x**		
Joly and Nikiema (2019)	**x**		**x**	**x**		**x**	
Suckling et al. (2021)		**x**	**x**	**x**	**x**	**x**	
Pleissner and Smetana (2020)	**x**	**x**				**x**	**x**
Groeneveld et al. (2021)	**x**	**x**	**x**	**x**		**x**	**x**

Mutuku et al. (2022) conducted a study in the counties of Nairobi, Kiambu, Murang'a, Kajiado, Machakos and Nakuru in Kenya. The farmers in the study area were smallholder farmers and their production activities were undertaken manually. BSFL farmers are still relatively few in the country. In-depth interviews were conducted, and a statistical analysis was performed. Results showed that the amount of the rearing substrate had a significantly positive relationship with the enterprise gross margin. It was observed that the cost of the substrate was very minimal, in some instances, the farmers obtained the substrate for free with the only cost associated with it being labour and transportation. Labour had a significantly negative relationship with the enterprise gross margin. It is presumed that more man-hours put into the enterprise without proper utilisation are resulting in diminishing marginal contribution of labour. Household size had a significantly positive effect on the enterprise gross margin. Labour is a very common input in BSFL production systems for activities such as larvae feeding, harvesting, sieving, and marketing. This probably explains the

[4] Van den Hoorn (2023) was published late 2023 after our literature analysis, but the thesis is relevant to our research question, discussing the economic viability of insect production for feed and food in Europe.

household size was positive influencing profitability, it is a source of cheap labour. Farm size, gender, level of education, age and the farming experience did not significantly influence profitability.

Munthali et al. (2023) conducted a cost-benefit analysis of BSFL as an alternative feed ingredient in Malawi. The objective of the study is to evaluate the financial feasibility of BSFL farming at three scales of production: individual farmers, cooperatives, and large-scale scale commercial farmers. The cost-benefit analysis is conducted by estimating the Net Present Value of benefits and costs. Components of costs and benefits and parameter estimates were determined by interviews and data collected from the Bunda pilot BSFL farm. Costs and benefits were calculated per larval or production cycle of 46 days. One year contains five production cycles. While most of the full first-year costs are in the initial setup, a full five-cycle year will require some additional variable costs. The Net Present Value was calculated for a period of ten years. Results imply BSFL farming is viable and feasible across scales of production. Findings should be validated by newer data. The authors state that farmers, entrepreneurs and industries should be provided with access to capital and formal credit. Although there are several formal credit institutions in Malawi, they are usually concentrated in urban areas; whereas most farmers prefer to borrow informally, for example from friends or relatives. There is a need for the government and other stakeholders to encourage the institutions to establish branches in rural areas.

Roffeis et al. (2018) have investigated the economic performance of ex-ante modelled insect-based feed (IBF) production systems operating in the geographical context of West Africa. A Life Cycle Cost analysis served as a basis to analyse and calculate the economic performances of using *Hermetia illucents* (black soldier fly, BSFL) reared on a mixture of brewery waste, chicken manure and water (and compare it with using *Musca domestica* (housefly), but this is beyond the scope of our research). The study explores the economic performance of a small-scale production system. The breakeven sale price was compared with the market prices of regular feeds. The system under investigation comprises the sourcing of raw materials, the insect rearing process, the separation of the IBF and residue substrate, and the processing of the final products. The IBF systems are compared based on costs associated with the provision of 1 kg IBF (which stands proxy for 1 kg whole dried larvae with a residual water content of less than 10%) and co-produced quantities of residue substrates (assumed marketable organic fertilizers) to a generic market in West Africa. The BSFL production system operates with artificial substrate inoculation, where substrates are inoculated with larvae from a captive adult colony (i.e. seed larvae). This results in a complex process cycle of six interrelated processes: substrate conditioning, egg production, larvae production, pupa production, separation (i.e. harvest) and drying. The production facility was assumed to be in close proximity to a poultry farm, to keep transportation needs to a minimum.

The results show that the economic performance is largely determined by the costs attributed to labour and to the procurement of rearing substrates (i.e. sum of substrate and transportation costs): 89% of total costs. The high labour costs (67% of total costs) are largely explained by labour inputs in the egg production unit. The operational activities relating to maintenance of adult colonies and the constant production of seed larvae equates to 63% of the total labour costs. Results show that the BSFL breakeven price is higher than conventional feeds such as palm kernel meal, soybean meal, cottonseed meal and fishmeal (Roffeis et al., 2018).

A sensitivity analysis showed that, as price variations of organic fertilizer affect the price of chicken manure, as well as trades residue substrates, the response of the break-even price is largely a function of the system's conversion efficiency, which is the efficiency with which the substrate is transformed by the larvae into the final product such as feed. Only a small relative change in break-even price is observed as chicken manure constitutes a minor component of the substrate mixture. It is noted that economies of relatively high conversion rates are seemingly offset by the higher costs for labour and rearing substrates. For example, artificial inoculation driving the production of BSFL facilitated a high conversion efficiency but raised production costs. And rearing processes with more than one substrate component require a higher level of operator training and cause additional sourcing efforts. However, given that the operational activities of trained staff members are to a large extent output-independent (management and monitoring efforts), a further upscaling of production permits the expectation of considerably lower breakeven prices (Roffeis et al., 2018).

Finally, it is noted that substrates that are already traded as a food or feed may benefit the system's conversion efficiency but are less cost-effective and should only be used in minimal amounts. With regards to transportation costs, application of IBF systems in close proximity to a substrate providing operation or markets appears recommendable. Considerations should also be given to feeding insects alive as this would save costs associated with drying/killing of larvae (i.e. labour and energy costs). To reduce the input of labour and associated costs, it requires up-scaling and the development of automation technology (Roffeis et al., 2018).

Liu et al. (2022) wrote a comprehensive review of the potential of BSFL for recycling organic wastes from livestock farming, manure bioconversions, parameters affecting the BSFL applications on organic farming, and process performance of biomolecule degradation. The last part discusses the economic feasibility. The data on economic aspects of BSFL organic waste bioconversion is so far limited. Detailed studies are usually not disclosed by companies. Profitability of the BSFL farming largely depends on the location of the operation, production scale, used substrate, and intended use of products (value-added products including fuel, feed and fertilizer). Due to high substrate acquisition costs, onsite production of BSFL biomass can improve the economic feasibility. It can be challenging to implement BSFL farming in some developing countries where waste production, collection, and separation is low. Another important aspect is the initial capital requirements to start BSFL farming. Financial incentives from governments and development programs could facilitate this process.

Joly and Nikiema (2019) reviewed several publications. They found out that most economic benefits associated with the BSFL technology lie in the fact that this treatment method valorises low-value organic waste into high-value protein at relatively low cost. As market prices for fishmeal and soybean meal are rising due to increasing demand, and feed accounts for 60 to 70% of the total animal production costs, the industry is actively investigating alternative protein sources. Different studies discussed both fixed costs (construction and equipment costs) and variable costs (labour, operation and maintenance of the facility, etc.).

BSFL does not require high investment costs compared to other organic waste valorisation methods, which makes it particularly suited to low and middle-income settings, characterized by limited financial resources. Regardless, BSFL farming requires investments. Large-scale BSFL facilities require less m2 to treat 1 tonne of waste, while smaller BSFL facilities need much more m2 to process the same amount of organic waste. Additionally, in medium-scale BSFL facilities the infrastructure costs, compared to the capacity or the area, are much lower than in large-scale BSFL facilities. This is because larger BSFL facilities are largely automated and are thus more efficient but on the other hand require larger investments (Joly and Nikiema, 2019).

Regarding the repartition of the infrastructure costs between the different units of a BSFL facility, it seems that the breeding unit is the costliest to build, 75-90% of the costs of equipment and materials accounted for the breeding unit, mainly the greenhouse (Joly and Nikiema, 2019).

The operation costs associated with a BSFL facility are low, and depend on the local climate, as breeding or rearing the BSFL in unfavourable conditions, such as Northern/colder countries, requires heating and potentially lighting, which result in higher energy costs. Estimating the life cycle cost in small-scale production has demonstrated that labour accounts for up to 65% of the operation cost. The overall economic performance of a BSFL waste treatment facility depends on various parameters such as the local climate (mainly temperature and relative humidity), the quantity, type and quality of waste processed, the capital and operation costs, the revenues from the sales of larvae and the waste residue, and potentially from waste processing. Two key parameters are the dry matter conversion rate and the time required to convert the waste. While energy costs are much lower in tropical countries due to climate, the market demand for the products, especially the larvae-based feed ingredients, may be higher in Northern countries, where a large part of the animal production industry is located (Joly and Nikiema, 2019).

Suckling et al. (2021) developed an optimization-based decision support tool to inform bioconversion businesses what locations to source surplus foodstuffs from, where to locate processing facilities and what business model to pursue. The work focusses on decisions around where to source surplus foodstuffs from, and where and how best to process them. Spent brewer's grains is used as a case study example of surplus

foodstuffs. The case study business is located in the southeast of the UK, and it has developed a 'small', semi-automated bioconversion unit (BCU) which may be located close to the sources of surplus foodstuff. Using small scale BCU (20ft container) in a distributed bioconversion model, initial capital costs may be reduced as compared to a single large scale, centralised BSFL rearing facility, and upscaling to meet future demand may be conducted in a more linear way. The production of BSFL is defined as taking place over two stages: processing and post-processing. The processing stage covers the rearing of BSFL on the surplus foodstuff. The post-processing stage covers the separation of the BSFL from the frass, and an optimal further step of drying the BSFL. Three business models are proposed and compared, which differ in whether drying is applied and where separation and drying take place. Results show that the alive & local model has much greater potential than either of the other two (dried & local and dried & central). Two factors contribute to this. Firstly, because water is not removed from the BSFL, this is less costly because drying is energy intensive. Secondly, the estimated selling price is almost the same per tonne, which reflects the higher value of live BSFL. The alive BSFL still contain a significant proportion of water. Hence the value per tonne of dry matter is much greater. The results also show that the two dried models have very similar net costs. The local model has less transport costs due to a lower mass of BSFL transported after drying. However, this is offset by an increased drying cost due to the greater amount of equipment used. These results are based upon a cost neutral (free) access to surplus foodstuffs and no income generated from frass sales, which might not be accurate. Both business models are more susceptible to changes in gate fee for the surplus foodstuffs than they are of frass price, because mass of surplus foodstuffs is more than frass generated. The margins of both models are highly dependent on the feed conversion ratio (FCR): the ratio of the mass of BSFL produced for a given mass of substrate. The dried & central model is more prone to volatility in the transport costs, because this model had two stages of transport, to the BCU and from the BCU to central headquarter. The most effective use of the BCU is upon a site where there are surplus organic materials produced, and on which the BSFL and frass may be used.

Pleissner and Smetana (2020) carried out an estimation of the economy of BSFL cultivations as food waste treatment with benefits (and compared it with the cultivation of algae which is beyond our scope). The paper is about the German situation. Food waste (water content 68%) from industry serves as substrate. Based on statistical data from the European union, 0.4 kg food waste (wet) is produced per capita and day. Collection and transport rely on existing infrastructure of local waste managers, and thus no costs regarding the purchase of vehicles are taken into account. The processes are designed to treat 53.6 ton (141,000 citizens) of wet food waste per day. This study relies on conditions that for one ton of food waste 0.06 kg of fresh young larvae is needed, which results in the production of 60 kg of frass and 9.57 kg of prepupae larvae. Development time from young larvae to prepupae can vary in the range of 15-52 days, depending on growth conditions. In this study 18 days is assumed. Results show that from 53.6 ton of wet food waste 3.46 ton of dried prepupae can be produced associated with the formation of 6.35 ton of dried fertilizer (frass) per day. The capital costs (investment costs) for the whole process were estimated at about 80.000 euro.

Operational costs are estimated at about 5,300 euro per day. The operational costs related to produce one ton of BSFL biomass are 450 euro. A relevant cost factor is the collection and transport of food waste. In this study 0.21 euro per ton of food waste was considered. This seems rather low, but includes already the fee possibly charged for the treatment of food waste. Private companies in Germany request for the disposal of potato peels and expired food in average about 80 euro per ton. Furthermore, this cost factor also depends on the catchment size area. In order to collect 56.3 ton of wet food waste a catchment area with 141,000 inhabitants is needed. Considering the effort needed for collection, this might be possible in urban areas, but challenging in rural areas (Pleissner and Smetana, 2020).

Groeneveld et al. (2021) explore whether it would be profitable for pig farmers to produce black soldier fly larvae on pig manure at Dutch farm level, if producing BSFL raised on manure would be legal (it is currently not allowed in the EU). The model assumes a farmer will buy starter larvae, apply them to process pig manure in a semi-automated manner and subsequently sell its output without much processing aside from potentially drying. The margins for the output of applying BSFL are set to 60% to indicate that the full final sales price might not completely go to the farmer, if the farmer is not the final link in the supply chain. Moreover, the margin makes sure that the following costs are indirectly included and expressed as a percentage of the final sales price: variable processing costs such as energy costs for drying, and variable marketing and logistics costs, such as packaging and shipping. Results are based on an average Dutch pig

farmer, who has to process pig manure of 1,671 adult pigs, which means about 900 ton of wet pig manure per year. This would result in about 89-104 ton of live BSFL, which could be turned into about 22-26 ton of dried insect biomass (25%) and 166-170 ton of the dried frass. Break-even prices of different scenarios (ratio of selling alive/dried insect biomass) turn out to depend strongly on the relatively high cost price of starter larvae (>70% of the total costs). Higher sales prices and delivering directly to the customer such that the margin can be increased will also make a positive profit more likely, just like increasing the production ratio, the price of frass, the manure disposal costs. Other parameters that have a noticeable influence on profitability are the price of labour and labour requirements. The potential of becoming profitable seems to be higher when the full grown larvae can be sold alive instead of dried. This is mainly due to the low dry matter percentage (25%) of BSFL. Another possibility would be to breed own black soldier fly starter larvae if the cost price would be below the market price of starter larvae. However, this requires more expertise and knowledge and raises the barriers to entry for pig farmers. Perhaps this could be done on a farmer cooperation level, where multiple farmers cooperate and manage a bigger facility.

Higher sales prices of live BSFL to chicken farmers may be warranted when considering arguments that state that BSFL provide added value as feedstuff, for example due to positive effects on animal well-being and egg quality of chickens. BSFL have different growth rates depending on the nutritional composition of the substrate. Therefore, mixing pig manure with a more nutritious waste stream (e.g. catering waste or other food waste) might enable profitability (Groeneveld et al., 2021).

3.1 Reflections on the case studies

As Table 1 above presents, the case studies from the literature show key factors relevant for economic feasibility of BSFL farming, which include labour costs, substrate costs including transport, costs of starter materials/eggs/young larvae, energy costs, the price of the final products, and the conversion efficiency. Here the findings are briefly reflected on for three relevant topics, namely the specific conditions of BSFL farming in LMIC, capital requirements, and considerations with respect to the scale of production.

3.1.1 Specific conditions for feasibility in LMIC

Labour is a very common input in BSFL production systems for activities such as larvae feeding, harvesting, sieving, and marketing. This probably explains that in LMIC the household size is positive influencing the profitability of BSFL production (Mutuku et al., 2022), it is a source of cheap labour in case of onsite production. Onsite production of BSFL reduces substrate acquisition costs as well. On the other hand, you probably lack efficiency because of lack of scale, automation, and probably having a suboptimal substrate composition. It can be challenging to implement large-scale BSFL farming in some developing countries where waste production, collection, and separation is low. The cost of collection and transport of food waste also depends on the catchment size area. Considering the effort needed for collection, this might be possible in urban areas, but challenging in rural areas. The operation costs associated with a BSFL facility depend on the local climate, as breeding or rearing the BSFL in unfavourable conditions, such as Northern countries, requires heating and potentially lighting, which result in higher energy costs. While energy costs are much lower in tropical countries, the market demand for the products, especially the larvae-based feed ingredients, may be higher in Northern countries, where a large part of the animal production industry is located.

3.1.2 Capital requirements

Another important aspect is the initial capital requirements to start BSFL farming. It is stated that financial incentives from governments and development programs could facilitate this process in LMIC. Farmers, entrepreneurs and industries should be provided with access to capital and formal credit. For example, although there are several formal credit institutions in Malawi, they are usually concentrated in urban areas; whereas most farmers prefer to borrow informally, for example from friends or relatives. There is a need for the government and other stakeholders to encourage the institutions to establish branches in rural areas. On the other hand it is stated that BSFL does not require high investment costs compared to other organic waste valorisation methods, which makes it particularly suited to low and middle-income settings, characterized by limited financial resources. Large-scale BSFL facilities require less m2 to treat 1 ton of waste, while smaller

facilities need much more m2 to process the same amount of organic waste. On the other hand, in small- and medium-scale facilities the infrastructure costs, compared to the capacity or the area, are much lower than in large-scale facilities. This is because larger facilities are largely automated and are thus more efficient (but require larger investments). Regarding the repartition of the infrastructure costs between the different units of a BSFL facility, it seems that the breeding unit is the costliest to build, 75-90% of the costs of equipment and materials accounted for the breeding unit, mainly the greenhouse. Probably stepwise upscaling is a good option. Suckling et al. (2021) show that by using small scale bioconversion units (20ft container) in a distributed bioconversion model, initial capital costs are reduced as compared to a single large scale, centralised BSFL rearing facility, and upscaling to meet future demand can be conducted in a more linear way.

3.1.3 Considerations with respect to scale

BSFL production and processing can, theoretically, be developed at different scale sizes, varying from smallholder scale (using residues/food waste from one or a few households/farms) to large, professional scale. Based on the literature, Table 2 presents considerations (benefits and hurdles/drawbacks) linked to three production scales. These considerations are mainly linked to the potential of creating optimal rearing conditions, fulfilling nutritional needs and managing safety including microbiological (incl. zoonotic), chemical (mycotoxins, heavy metals, drugs, pesticides, processing contaminants, etc.) (Hoek et al., 2022).

Table 2 Summary of considerations with respect to the scale of BSFL farming.

Scale	Motivations/benefits	Potential hurdles
Smallholder farmer	- Can feed on household food waste - The household can directly manage the safety of the substrate (food waste) - Easy to harvest - Produces frass (humus) that can be used as fertilizer - Create value from waste - Use the BSFL as input on farms, create closed loops	- Quality of food waste/substrate is relatively poorly controlled because of possible lack of knowledge and quality management systems - Composition of the substrate (fat, protein) - Variability (volume and nutritional value) is higher than when waste streams of multiple households/suppliers are combined - Safety of the substrate and produced larvae (amongst others threats of zoonoses when using manure and mycotoxins in spoiled food residues/waste) - Access to BSFL starter larvae - Viable business model, also considering that safety measures may be required (Surendra et al, 2020; Vandeweyer et al, 2021). - Competition with direct feed to fish, poultry and pigs vs waste/feed for BSFL
Regional, larger farms that produce partly for sales, party for own use in other farm activities	- Could be startup/growth model - Could be specialising on starter material for small-scale producers - Efficient collection of food waste	- Startup/growth model will require substantial start-up investments and may be risky
Large scale specialised in BSFL production	- Relatively low investment costs and high product-value when used as organic waste management strategy - Can be used as animal feed, processed into fuel, and/or applied as organic fertiliser - Lower global warming potential than conventional composting (but few studies) - Economies of scale for investments in rearing and processing equipment	- Relatively new on industrial scale - Depends on stable quantity and quality of food waste availability - Management/control of safety of collected food waste - More research needed to identify safe, efficient, environmentally sustainable and profitable ways to carry out the technology (specifically: important to determine efficient treatment techniques, optimal environmental conditions for the larvae and improve methods of BSFL colony management > process where seed larvae are produced in called BSFL colony) - Crucial to have control and knowledge of all stages in the process for an industry that handles tons of food waste - Need to limit the risk of process failure due to parasites, pathogens and pests

4 The potential of BSFL farming to contribute to food security in Kenya

Through the literature review we identified relevant factors for economically feasible BSFL production in LMIC. In this chapter we quantitatively explore the potential of BSFL farming to valorise FL/FW into proteins for human consumption, and thereby its potential to contribute to food security. We do so for the Kenyan context because of the traction of BSFL farming in the Kenyan context, the availability of FL/FW, and the food security needs.

For estimating the potential contribution of producing BSFL from FL and FW, in the below analysis the estimates of volumes of available FL and FW streams are considered. For this analysis it is most essential that representative figures for FL and FW are used. Considering that from different definitions large differences in estimated volumes are derived, we observe that:

- One recognized reference, Porter et al. (2016), uses a very broad definition of FL and FW: all harvested food intended for food that does not reach the retail stage is considered FL; all food received by retail but not sold in the regular way as well as all wastes induced by the consumer are considered FW. It is unclear from the paper whether products that are donated or traded at reduced prices (possibly alternative outlets) are also included in Porter's definition of FL. Surely destinations feed (and possibly other productive uses different from food) are counted as FL and FW in Porter's definition.
- On the other side, in FAOSTAT Food Balance Sheets (FBS) (FAOSTAT, 2022) values for FL and FW are provided that have no food, feed, seed or processing destinations. Presented volumes of FL and FW describe all products that are wasted in the chain from post-harvest up to, but not including, households.

The large deviations between these references are reflected in the high differences of the estimated FL and FW according to these: for instance for vegetables Porter's FL/FW estimates are about five times higher than in FAOSTAT-FBS data. Porter's FL/FW estimations are for the continent of Africa, while the FBS data is available at national (Kenya) level.

Table 3 (next page) presents the results of the analysis for a set of product categories (sugar crops and oil crops are neglected here: sugar cane is not considered very suitable from a technical perspective; the volume of lost oil crops is very low according to FAOSTAT-FBS). Below the total protein loss per year is presented, as well as the calculated protein yield through BSFL production and through egg production from FL-fed BSFL. These calculations are based on the estimated annual volume of lost products after harvest until sales to the consumer and estimated protein content. The results overlook that for practical reasons, including food safety issues, not all streams can be utilized; the analysis is intended for obtaining a notion on potential contribution to food security.

Table 3 Estimated annual volume of FL/FW for selected food product categories in Kenya according to FAOSTAT FBS, content of proteins and protein yield in BSFL and protein yield to eggs when the BSFL are fed to laying hens (volumes in kton/year).

Product category	Average volume FL/FW (average 2019-2021)	Protein content* (g/kg)	Volume of Proteins in FL stream	Estimated protein yield in BSFL production	Estimated protein yield (to eggs) when BSFL are fed to laying hens
Cereals	186	62	11.5	4.6	1.2
Starchy roots	305	15	4.5	1.8	0.5
Pulses	127	212	27	10.8	2.9
Vegetables	301	13	3.9	1.6	0.4
Fruits	319	2	0.6	0.2	0.1
Eggs	15	124	1.9	0.8	0.2
Milk	577	33	19	7.6	2.1
TOTAL			68.5	27.4	7.4

* Values for common representative products in Kenya are chosen:

- for cereals: maize
- for starchy roots: potatoes, cassava and sweet potatoes
- for pulses: peas
- for vegetables: tomatoes, unions, green cabbage, carrots, spinach
- for fruits: apples

Assuming that practical (safety, quality, chain development, etc.) challenges could be solved and that the valorisation would be legally allowed, the valorisation of FL/FW with BSFL could contribute to additional food production. Typical yield (in terms of dry matter) of diverse pathways (like a blend of supermarket returns and food waste from university dining hall, Fung et al., 2019) to food is estimated as follows (through the method described by Broeze et al., 2024):

- direct application of FW/FL as pig feed: 19.7% (with protein efficiency 17.0%);
- direct application of FW/FL as layer chicken feed: 27.4% (with protein efficiency 27.0%);
- direct application of FW/FL as insects feed: 28.6% (with protein efficiency 40.0%);
- indirect: via insects, which are consequently applied as layer chicken feed: 9.1% (with total protein efficiency 10.8%).

These estimates are based on average productivities in intensive production systems in The Netherlands and comparable contexts. For less intensive production systems somewhat lower efficiencies are expected, but the ratios between the values are still considered applicable.

Comparing the above percentages, applying a FL or FW stream as feed for insects is quite efficient. Consuming insects directly as food is a more efficient way of using FL and FW as a protein source in new food products compared to consuming pigs or chickens fed with FL and FW. The results show that the application insect has quite comparable yield to food as application as chicken feed. However, the path via insects which are thereafter used as chicken feed is substantially less efficient. This means that this pathway is only recommended for food residues/waste streams that are unfit as direct chicken feed (because of e.g. microbial safety status, legal hurdles or volume). In such cases, BSFL can – with indicatively efficiencies as indicated above – contribute to food security.

We conclude that theoretically from selected wasted products, 27.4 kton BSFL proteins can be produced. The total annual protein intake by the Kenyan population is estimated around 1.3 million tons proteins (Groot et al., 2021; Axmann et al., 2024). In this way BSFL produced protein can fulfil around 2% of the annual national requirements of protein in food. This contribution will be much lower (7.4 kton BSFL proteins fulfilling 0.6% of annual protein intake) when BSFL are applied as feed for layer hens and consequently eggs as human food, as shown in the last column in Table 3.

Insects are often considered promising resource for nutrition security, the estimated amount of insect protein from the FL streams may sound disappointing. This relatively low number compared to the current protein intake can be explained as follows: The available volumes of FL/FW streams are less than 10% of the food

volume that ends at the households. With an eye on the limited protein conversion efficiency of insects (as counts for other livestock), the total protein yield of the FL/FW fed BSFL is limited to maximum few percents of the total food production.

Altogether, the potential contribution in percentages to protein supply at a national level from BSFL production on FL/FW along supply chains that have no food, feed, seed or processing destinations can be considered relatively small. Nevertheless, the amounts can be considered significant and FL/FW valorisation with insects has potential.

5 Conclusions

This report presents the analysis of a cost-effective logistic design (Chapter 3) is combined with quantitative estimates of potential contribution to food security through BSFL reared on FL/FW (Chapter 4). There are limited case studies available from this perspective; this report is considered a valuable addition to available technical, safety, and regulatory explorations of BSFL farming.

In Chapter 3, the case studies from the literature show key factors relevant for economic feasibility of BSFL farming, which include labour costs, substrate costs including transport, costs of starter eggs/young larvae, energy costs, the price of the final products, and the conversion efficiency of FL/FW into feed and food. BSFL farming in LMIC can be promising because of favourable climatic conditions compared to colder climates, which reduces the need for energy, but overall production costs can be high, just like the capital requirements. From a logistical perspective, production closer to peri-urban and urban areas compared to rural areas might be beneficial for creating economies of scale, access to the FL/FW, and available infrastructure. However, animal production and animal feed markets are predominant in rural areas. Capital requirements for BSFL farming are significant, but typically lower than other organic waste valorisation methods. Various motivations/benefits as well as hurdles are summarised for three production scales: small scale farming, regional farming, and large-scale farming.

In Chapter 4, the quantitative analysis is presented based on estimated volumes of food products that are currently managed as waste (thus, that have no functional use as food, feed or added-value non-food use in the current system) in Kenya. It was found that theoretically from selected wasted products, 27.4 kton BSFL proteins can be produced, which fulfils around 2% of the national human protein intake. If the BSFL are fed to layer hens, a maximum 0.6% extra human proteins can be produced in eggs. Altogether, the potential contribution in percentages to protein supply at a national level from BSFL production on FL/FW along supply chains that have no food, feed, seed or processing destinations can be considered relatively small. Nevertheless, the amounts can be considered significant and FL/FW valorisation with BSFL has potential, but relevant logistical, market, and cost-effectiveness considerations should be regionally explored prior upon initiation, for diverse production scales.

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