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FROM PILOT TO FULL SCALE OPERATION OF A WASTE-TO-PROTEIN TREATMENT FACILITY

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ABSTRACT

Recycling of municipal organic waste material (biowaste) still remains fairly limited especially in low and middle-income settings although this is by far the largest fraction of the municipal waste generated. A fairly novel approach is rapidly establishing itself and concerns biowaste conversion by larvae of the Black Soldier Fly (BSF), *Hermetia illucens*. The popularity of this approach links to the promising opportunities of using the harvested insect larvae as a protein source for animal feed thus providing a valuable alternative to conventional animal feed that requires a large amount of increasingly scarce resources (water and land for soya meal, and fish catch for fishmeal). The research project presented here has developed relevant and easily applicable guidance for practitioners who aim to establish a commercial facility, learning from pilot scale activities in Indonesia and then using modelling and up-scaling assumptions to highlight challenges and opportunities of larger scale implementation.

1. INTRODUCTION

In low- and middle-income urban settings, the organic biodegradable matter (=biowaste) constitutes the highest overall waste fraction with 50-80 percent of the total municipal waste amount generated in weight (Wilson et al. 2012). If not managed in a proper way – as is typical for many low- and middle-income settings - biowaste affects the environment and public health in a negative way. Rotting waste creates olfactory nuisance, attracts vermin and other disease transmitting agents. Furthermore, uncontained and untreated leachate from biowaste contaminates surface and groundwater supplies (Reddy and Nandini 2011). In uncontrolled disposal sites decomposing biowaste generates methane contributing to greenhouse gas emissions (Bogner et al. 2008). Management of biowaste is still fairly limited, especially in low- and middle-income settings, although a paradigm shift towards a circular economy focused on 'closing loops' through recovery, is a promising concept. Biowaste in a circular economy tackles nutrient resource scarcity or the need for renewable energy. The shift to biowaste recycling in municipal solid waste management is however limited by the potential net value typically obtained, as the costs of obtaining good quality waste are high and the revenue stream from sales of the waste derived product is either limited or complicated to ensure on a regular basis. From a research perspective however, biowaste treatment has already attracted considerable interest and many potential solutions exist (Lohri et al., 2017).

This paper focuses on a fairly novel approach of biowaste treatment based on waste conversion by insect larvae – namely using the Black Soldier Fly (BSF), *Hermetia illucens*. This approach comprises a transformation of biowaste into insect protein and insect oil. The process of converting biowaste into insect protein has already been studied by many researchers. The research has focused predominately on the biological mechanisms in the process and at lab or bench scale, for instance around the topics of mating behaviour or survival rates in the different life stages (Lohri et al., 2017). Although important, such research has limited use for practitioners. Implementation of a BSF-treatment approach for low and middle-income setting relies on practical evidence at either neighbourhood or industrial scale. It is this knowledge of operational steps, monitoring and control protocols, as well as equipment reliability and appropriateness, that helps stakeholders in waste management implement, operate and sustain a treatment facility successfully. There is some evidence that private enterprises are already investing into this technology, but they are interested in keeping a competitive edge and are quite secretive on all practical aspects of operating such a facility in a cost-effective way. This hinders an academic debate and open exchange but more importantly is a major barrier for widespread dissemination and replication. Filling this gap in open-source practical

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knowledge is the objective of a recent publication that is available for download online (www.sandec.ch) as: Black Soldier Fly Biowaste Processing - A Step by Step Guide (Dortmans et al. 2017). The paper at hand presents some of the results contained in that publication but goes a step further by also providing additional information on financial considerations and cost-revenue streams for a small scale treatment unit and then discussing implications for scaling up to a larger industrial scale.

2. MATERIALS AND METHODS

The particular interest of the study presented in this paper focuses on two main and strongly interlinked management aspects of a BSF waste treatment facility: 1) the operational activities and their sequencing to ensure that waste can be treated reliably and consistently every day; and 2) the associated costs involved in establishing, operating, and maintaining a BSF treatment facility of a certain scale in a given local context.

To develop the list and sequence of activities, tasks and related equipment needs, the project used an experimental approach at pilot level. Two ongoing applied research projects provided the experimental backbone resulting in the data presented here. FORWARD is a 4-year-long applied research project with a focus on integrated strategies and technologies for the management of municipal organic solid waste in medium-sized cities of Indonesia. Among other activities the project designed, implemented and operated a pilot-scale BSF waste treatment facility at a local wholesale market. It operated with an incoming vegetable and fruit waste amount varying between 0.5-1 ton per day. This BSF pilot facility allowed to derive "Standard Operating Procedures" for further dissemination (Dortmans et al, 2017) and currently also acts as a showcase and training site. The FORWARD project is funded by SECO, the Swiss State Secretariat for Economic Affairs, under a framework agreement with the Indonesian Ministry of Public Works & Housing (PU-PeRa). A second research project - SPROUT - is a three-year project with a focus on hygienic aspects, design and operation of BSF treatment units, quality of products (feed and fertilizer), post-harvest processing regarding feed quality and product safety, business models for BSF waste processing, and evaluation of the environmental impact of BSF waste processing compared to other biological treatment options. SPROUT is a multi-national project with SLU (Swedish University of Agricultural Sciences) and Eawag (Swiss Federal Institute of Aquatic Science and Technology) as main research partners and Pacovis AG from Switzerland as the partner from industry and it is funded via the EU-program ECO-INNOVERA, the Swedish Research Council Formas, the Swiss Federal Office for the Environment FOEN, and Pacovis AG.

For assessing and estimating cost-revenue aspects, we used the work measurement technique of time-motion studies applied to the facility in Indonesia (Dortmans, 2015). As labour costs are the most dominant variable costs, it was crucial to understand how much work load was utilized for which task in the treatment facility. Furthermore, the accounting method of activity-based costing (Weygandt et al., 2012) was used to structure cost types in each operational step of the facility. Activity-based costing (ABC) is a method that looks at the activities that a firm performs to finalize a product and then assigns multiple cost types and cost drivers to each defined distinctive activity unit. In the BSF case these distinctive functional activity units are those that together contribute to "treating waste and producing larvae and residue". These units were established in an experimental setting and are used to structure the standard operational procedures. Activity-based costing can help analyse the relationship between costs, activities and products. It can assign capital costs and variable costs to such units to give better insight on how these units compare to each other, and where optimization potential is highest for instance by introducing a certain automation and machinery. In ABC indirect costs, linked to management and office staff for instance, are sometimes difficult to attribute to a unit. That is why this method is particularly relevant in the product manufacturing sector. In the BSF case the products being "manufactured" are the larvae and the residue. Depending on how costs respond to a change in a business activity, they can be classified as fixed, variable, or mixed costs (Weygandt et al., 2012). Fixed Costs, as the name implies, do not change regardless of the activity level. They are independent and remain the same even if there is an increase or decrease in production, but only as long as the production does not require additional machinery. Examples of fixed costs are capital costs such as construction and land costs or periodic fixed costs like depreciation, rent, insurance, and cost of capital. Variable costs are linked to the activity level and thus change directly and proportionally with the goods or services produced. Typically, direct material, direct labour, and water or electricity can be categorized under such costs. Mixed Costs consist of both fixed and variable costs. These costs will change with the activity level but not proportionally with the goods or services produced. Mixed costs are not relevant for production facilities of this type and were neglected in our study. A framework of modelling the costs was developed based on defined units and using excel spreadsheet software. Besides the primary data sources from the experimental sites, secondary data sources were collected from literature. For specific equipment, also quotes and tenders from the industry were obtained and included. Two scenarios were then analysed for the geographical context of Indonesia, a 1 ton and a 60 ton per day incoming waste facility.

3. RESULTS AND DISCUSSION

3.1 Operational aspects of Black Soldier Fly waste treatment

The Black Soldier Fly (BSF), *Hermetia illucens* is of the dipteran family Stratiomyidae and can be encountered worldwide between the latitudes of 40°S and 45°N. The female fly lays eggs close to decomposing organic matter and into small, dry, sheltered cavities. On average, the eggs hatch after 4 days and the emerged larvae, which are barely a few millimetres in size, will search for food and start feeding on the organic waste nearby. The larvae then feed on decomposing organic matter to grow from a few millimetres size to around 2.5 cm length and 0.5 cm width. Under optimal conditions and ideal food quality and quantity, the growth of larvae will require a minimum period of 15-17 days. BSF larvae however have the ability to extend their life cycle if conditions are unfavourable making it a very resilient organism. When reaching the final larval stage, as prepupa, it moves out and away from the food source and to a dry, shaded and protected environment for pupation. Pupation takes around 2-3 weeks and ends when the fly emerges from its pupa shell. After emerging, the fly lives for about one week. As a fly, BSF do not feed, but will only search for a partner to copulate and then lay eggs. In this life stage, natural light and a warm temperature (25-32°C) is required.

For a BSF processing facility the goal is to optimize this natural life cycle using engineering principles. Based on this concept, we suggest to differentiate distinct processing units as described below and shown in Figure 1.

The BSF rearing unit ensures that a reliable, consistent and sufficient amount of small larvae is continuously available to inoculate the daily amount of biowaste received for processing. One fraction of the larvae is kept in the rearing unit and bred in a controlled manner to ensure a stable population. A well-engineered BSF nursery monitors the survival rates at every step in this cycle and keeps track of the colony's overall performance. With this information, it controls the number of prepupae that are allowed to pupate which allows control of the number of flies that emerge, as well as egg packages deposited, and number of larvae hatchings. In the rearing unit two type of cages can be distinguished: the "dark cage" and the "love cage". Pupation containers with moist soil-like substrate (matured compost) are placed inside a "dark cage". The dark environment, provides the pupae with sufficient protection from the changing outside environmental conditions (moisture, temperature, movement of air, etc.). Due to the darkness inside the cage, the emerged flies will remain motionless. Emerged flies are collected from the dark cage by connecting this dark cage to another cage, which is not darkened, through a tunnel. A light source set at the end of the tunnel will attract the flies to fly from the dark cage into this undarkened "love cage". The love cages each contain a box with a smelly substrate attracting the flies to induce egg laying and a media for laying eggs into, as well as a wet cloth to allow the flies to hydrate. The love cages are then exposed to (indirect) sunlight to stimulate mating. Eggs deposited are harvested and deriving hatchlings are fed for five days in a controlled environment before they can be put into the BSF waste treatment unit.

In the waste pre-processing unit the quality of the incoming waste is controlled to avoid hazardous or inorganic substances. Then a reduction of the waste particle size follows. Particles of smaller than 1-2 cm in diameter are ideal as BSF larvae do not have appropriate mouthparts to break apart larger waste pieces. This helps to speed-up the BSF processing time. In the case of high water content in waste (moisture of 70-80% is best for the larvae), dewatering may be necessary whereby blending different types of biowaste with complementing (lower) moisture content is also an option.

In the BSF waste treatment unit a part of the waste is transferred to empty containers (so-called larveros) where small larvae from the rearing unit are added. The other part of the waste is added to existing larvero containers with already larger larvae. As a rule of thumb, we work with 10,000-12,000 "five-day-old-larvae" (5-DOL) added into one larvero container with a size of 40x60x17 cm. While the larvae feed and grow, more waste is added to the same larvero container on day 5 and again on day 8, adding up to a total of 15 kg of fresh waste per larvero. The larvae are harvested after 12 days. The individual larvero containers can be stacked on top of each other to maximize the use of the space available, however it is important to leave space between the containers to allow sufficient air ventilation (Figure 2).

Finally, in the processing and refining unit, larvae and residue can be further processed depending on local market demand. They may be sold alive to customers (e.g. reptile farms or bird market) or processed to feed pellets to establish a blend, which meets the nutritive requirements of the targeted animal (broiler chicken, layer hen, different

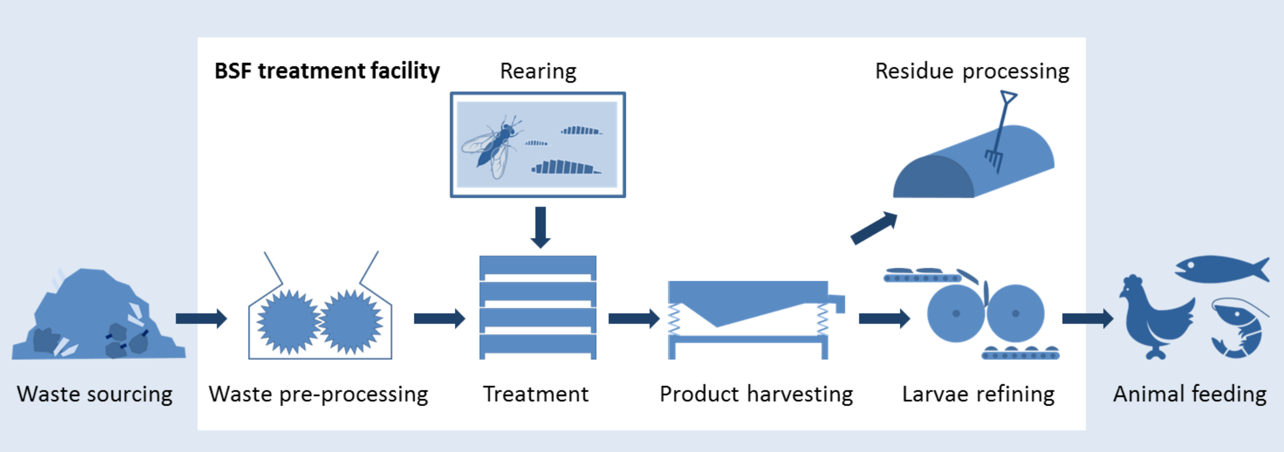

FIGURE 1: The different units of a BSF treatment system (Dortmans et al, 2017).

FIGURE 2: Stack of larvero containers with ventilation frames in-between levels (Dortmans et al, 2017).

fish species). In most cases, larvae will need some form of post-processing to ensure they can be sanitized, stored and transported easily to the respective customers. Sanitising involves killing off any bacteria, which might be adhering to the larvae skin and ensuring that the larvae empty their gut which contains only partly digested residue. We recommend dipping the larvae into boiling water as this kills them instantly and sanitizes the product. A storable product requires a water and fat content of below 10%. Sun drying is suitable to reduce water content and the fat content can be reduced using an oil press. The waste residue has similar characteristics as immature compost and therefore requires post-processing. Composting the residue is the simplest approach, but an alternative is vermicomposting or adding it into an anaerobic digester.

3.2 Overall siting considerations

The following points must be taken into consideration when selecting an appropriate site for a BSF processing facility:

- Water and electricity supply and wastewater management options should be available.
- Environmental buffers that separate the facility from the surroundings should be ensured (e.g., open areas, trees, fences) as visual barrier as well as to minimize impact of the slight odour emission
- Sufficient, regular and predictable amounts of fresh biowaste (source segregated) should be available at lowest cost possible. Although this is not discussed in further detail in the paper, this aspect is crucial. For the city waste manager that faces the challenge of large amounts of household waste and is in search for a treatment solution, household segregation is a key determinant to obtain good quality organic waste for BSF treatment. This is not a simple endeavour. On the other hand, an easier way to start with BSF waste treatment is to target business and industrial enterprises that generate large amounts of already quite “pure” organic waste for instance slaughterhouses, breweries, agroindustry, supermarkets, vegetable and fruit markets or restaurants.
- A closed and ventilated room is required for the rearing unit but also sunlight is required to ensure mating of flies. A sheltered area without direct sunlight is needed for the treatment containers as well as office, lab space, toilet and hygiene facilities.

3.3 Costing considerations

A BSF-treatment facility can produce 200 kg (wet weight) of grown larvae per ton of incoming waste processed. Results of the financial analysis show that total annual costs, assuming one ton of processed waste per day and an average equipment depreciation of 3 years, amounts to around 16,700 €. The land costs and building construction was however not included in this calculation, as for the case of Indonesia the land and building were existing and provided. All activities related to the rearing unit amount to up 31% of these costs. Labour costs amount to 45% of the total costs whereby other variable costs such as electricity, water and chicken feed for the nursery only amount to about 12% of the total costs (Table 1). This scenario reflects a situation where all machinery is kept to the minimum requirement and where all processes rely as much as possible on manual labour (1 person in the rearing unit and 2 persons for all the other units). One aspect to consider is the maximum operating capacity of the equipment. In other words, much of the equipment is designed for larger capacity and at these small scales of one ton of waste per day would be utilized under capacity therefore increasing the production costs. Another aspect to consider is that the labour requirements at the rearing unit are least dependant on scale of production. With a similar setup at the rearing unit, the capacity can easily be increased to around 5 ton/day without much change in cost.

With an increase in scale to a 60 ton/day facility, both labour and equipment cost will obviously increase. Here some economies of scale come into effect. For instance when analysing labour requirement per ton of waste, a significant reduction from 6 staff per ton to 0.58 staff per ton can be shown. Given the low unskilled labour costs in In-

TABLE 1: Unit costs for the rearing unit and other units based on a 1 ton/day BSF facility.

Activity Unit	**Euro/Year** 1 t/day	**% of total**
Rearing units		31%
• Labour	2,483	
• Consumables	1,095	
• Annual equipment costs	1,526	
Treatment units		56%
• Labour	4,966	
• Consumables	881	
• Annual equipment costs	3,545	
Indirect costs	2,174	13%
Total	**16,670**	**100%**
Labour		45%
Consumables		12%
Equipment		30%

donesia however, the impact of this on total costs is lower than in a high labour cost situation such as Switzerland. Furthermore, technology and equipment cost, which will be unavoidable at this larger scale, do not vary much between Indonesia and a high-income country. The ratio of equipment to labour cost will thus increase in the large-scale facility and this will increase dependency on skilled operators, skilled maintenance and availability of spare parts. All these aspects are well known as typical barriers that reduce the technical feasibility of a facility in low and middle-income countries.

Regarding revenue sources, reliable data is not yet available as markets are still novel and price not well established. Furthermore, the small amounts of larvae currently produced limits the potential of market exploration and at this stage only caters to specialized niche markets. Based on current sales revenues of 0.35 € per kg of dry BSF larvae could be expected.

4. CONCLUSIONS

The structure of activity units in a BSF waste treatment facility is helpful not only for defining standard operating procedures and material lists but also to better assess the costs associate with different tasks. The cost analysis of the BSF production gives important insights concerning the economic feasibility of this technology. Closely assessing the different components has made it obvious that certain production steps include sizing issues when being brought to a larger scale. These steps are namely the rearing unit and the treatment unit. Insights from professional process analysts could be of additional value as upscaling opportunities are not yet fully exploited and different sets, sizes and arrangements of the machinery could significantly decrease costs. In general, cost behaviour is always on the side of the economies of scale of bigger facilities. The conducted calculations emphasize most opportunities and drawbacks and lay open where and when costs do not behave proportionally. Besides showing upscaling benefits in most areas, the legal uncertainties and inflated capital costs connected to a 60 tonnes BSF facility might still shy away public and private stakeholders from investing in such a project. The changes in legislations and common perception of insect meal as a source of protein are important determinants of the future success of the BSF technology. Although the cost difference may not justify the administrative and logistic pitfalls included in producing in Indonesia and other countries in the region might be even more attractive financially, the investment seems equitable, regardless, if the financial incentive of producing BSF larvae meal is secondary and the purpose of the facility focuses primarily on adequate waste management.

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