Journal of Insects as Food and Feed, 2023; 9(3): 303-316

Modelling the financial viability of centralised and decentralised black soldier fly larvae waste processing units in Surabaya, Indonesia

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Received: 23 February 2022 / Accepted: 14 May 2022

RESEARCH ARTICLE

Abstract

Black soldier fly larvae (BSFL) waste processing has proven to be a promising approach, which can be applied in centralised or decentralised settings. Financial considerations however still remain undisclosed given business secrecy. Building on the experiences of a facility and operational setup in Indonesia, this study conducted an in-depth cost analysis using methods such as time motion studies, activity based costing and a mass flow balance to evaluate business models. Thereafter followed an analysis of different scenarios on how to integrate the approach into the solid waste management system of Surabaya, Indonesia assuming different degrees of decentralisation with market rates and prices from 2020. Results show that a centralised plant, managing all steps of the BSFL process (Scenario 1), achieves the highest net present value (NPV), mainly through the economy of scale. When BSFL waste treatment is conducted using a decentralised approach, close to the waste sources, and the nursery and post-processing of larvae remains at a central location (Scenario 3), other benefits besides the still positive NPV can be shown. Such a scenario for instance would reduce the spatial footprint of the central facility, create jobs within the communities and reduce the transport costs and total costs for the municipality. Another scenario (Scenario 2) hypothesises a decentralised waste treatment as well as post-processing of larvae at the same decentralised location increasing storability and the value of products. Although this achieves higher NPV values compared to Scenario 3, it requires larger scale units to achieve financial viability. Coordination and facilitation by local government can further strengthen a network of decentralised BSFL treatment plants, as the city authorities could focus on operating a centralised nursery (Scenario 2), supplying young larvae at low cost or free of charge to increase the financial viability of the decentralised plants treating the waste.

Keywords: organic waste treatment, biowaste, *Hermetia illucens*, BSFL recycling, business model

1. Introduction

Most low and middle-income countries worldwide are now pursuing principles of a circular economy as an underlying strategy, which also guides and informs municipal solid waste management towards taking advantage of waste valorisation and recycling for boosting developing economies (Ferronato *et al.*, 2019). Understanding characteristics of business model structures and innovations in this regard is important not only to ensure financial sustainability, but also to best integrate these into the strategy of municipal solid waste service provision of local governments with a focus on increasing recycling rates. Key activities, partnerships, and cost structures are main building blocks that allow the design of a business model aligned to the principles of circular economy (Lewandowski, 2016). A better understanding and adaptation of these building blocks allow improving process control, and technology changes (activities), choice of partners along the value chain and supply chain (partners), as well as financial changes including the value of incentives for customers (cost-revenue structure).

Indonesia, similar to other low and middle-income countries, is tackling a municipal solid waste (MSW) crisis with a steadily increasing amount of waste being generated and the need to improve and integrate its waste management systems (Muhamad *et al.*, 2020; Zurbrugg *et al.*, 2012). The Indonesian government acts and set the aim to reduce municipal solid waste by 30% on a national level by 2025 (Government of the Republic of Indonesia, 2017). At local level, the city of Surabaya is a pioneer with regard to waste reduction and recycling initiatives (Muhamad *et al.*, 2020), with its own program Surabaya Green and Clean (SGC). The SGC program has shown to reduce the waste amount from 2005 to 2008 from 1,500 to 1,150 metric tons per day, a reduction of 23%, by motivating neighbourhoods to practice waste reduction, waste sorting and composting (Pratono *et al.*, 2017). Additionally, the introduction of material reuse facilities has increased waste recovery (Muhamad *et al.*, 2020). Organic waste is the largest fraction with 72.4% of the municipal solid waste generated per day (Dhokhikah and Trihadiningrum, 2012), thus showing a high potential for increasing waste reduction through organic waste treatment.

Black soldier fly larvae (BSFL) are seen as a promising organic waste processing technology, due to the ability to reduce waste while creating a valuable product (Joly and Nikiema, 2019). Up to 80% of waste mass can be reduced and turned into larvae biomass with a biomass conversion rate (BCR) of 20% based on dry matter (Diener *et al.*, 2011). Due to its high fat and protein content amongst other properties, BSFL have shown to be an ideal source for animal feed and pet food (Chia *et al.*, 2019; Mouithys-Mickalad *et al.*, 2020). BSFL can be processed to various products, such as dried larvae, protein meal, oil, biodiesel, chitin, or used directly as unprocessed fresh larvae (Joly and Nikiema, 2019). The potential to build a BSFL plant treating organic waste, using a simple and low-tech approach, makes it an interesting technology for low- and middle-income settings. This was demonstrated with the BSFL pilot plant built and operated in the scope of the FORWARD project in Surabaya, Indonesia (Dortmans *et al.*, 2021).

In Indonesia, MSW is collected from households with small vehicles and transported to transfer stations, where the waste is then temporarily stored before being hauled with larger trucks to final disposal, mostly at landfills. Such a waste transportation system can typically account for 60-70% of total costs of the MSW management system (Kaza *et al.*, 2018). Upgrading a transfer station to a material recovery facility (MRF) can lead to a reduction of transport costs and an increase in landfill diversion by re-use and re-cycling as presented by Muhamad *et al.* (2020). At this stage there is also the potential to use BSFL to treat organic waste and increase revenue creation with high value products. Diener *et al.* (2015) showed the potential scales of a BSFL plant from small to large scale and the benefits of a semi-decentralised unit to improve the solid waste management system. Chia *et al.* (2019) argued that establishing the BSFL process at a community level, where a smallholder farmer operates a BSFL farm, can create inclusive business models that improve the livelihood of communities. Thus, there are various ways in which BSFL plants can be integrated into the waste management system, from small-scale decentralised units at community level, to larger scale units at MRF sites. A financial evaluation however is needed to better understand the viability of each setup.

To date there is still very limited published data on the cost implications and viability of BSFL operations in general and at different scales (Joly and Nikiema, 2019). As private companies enter the BSFL commercial space, very limited reliable data on costs of the BSFL process available given the interest of the companies to maintain a competitive edge (Zurbrügg *et al.*, 2018). Additionally, information on potential revenues from BSFL products vary as there is yet no well-established market for the products (Joly and Nikiema, 2019). Market studies show that higher profits can be achieved if BSFL products are sold for the pet food market as compared to selling as livestock feed (Caruso *et al.*, 2013).

The objective of this study was to analyse the costs associated with the BSFL process based on an existing plant and the example of the solid waste system of Surabaya, Indonesia, to understand the potential revenues and to develop a generic business model that can be used to evaluate scenarios of a BSFL approach with different degrees of integration, from centralised to decentralised units.

2. Materials and methods

Black soldier fly larvae process and processing units

The BSFL process has several characteristic steps, which are described in detail by Dortmans *et al.* (2021) and are shown in Figure 1. A nursery unit (Unit-N) maintains the full BSF life cycle from fly to eggs to larvae to pupae. The neonates are reared until 5 days old (5-DOL), on a special feed at the nursery consisting mainly of chicken feed. Thereafter the majority of 5-DOL are moved to the treatment unit (Unit-T) to feed on waste. A small fraction of the 5-DOL is kept at the nursery to grow until pupation thereafter pupate and emerge as flies. Organic waste is delivered to the BSFL plant, sorted and shredded (pre-processing Unit-W). before being moved to the treatment unit (Unit-T) where the 5-DOL are added to the waste.

At the treatment unit the larvae feed on waste for another 12 days until the larvae are 17 days old (17-DOL) and ready for harvest. These 17-DOL are then separated from the waste in the harvesting unit and sold either directly as fresh larvae or further processed in the post-processing and refining

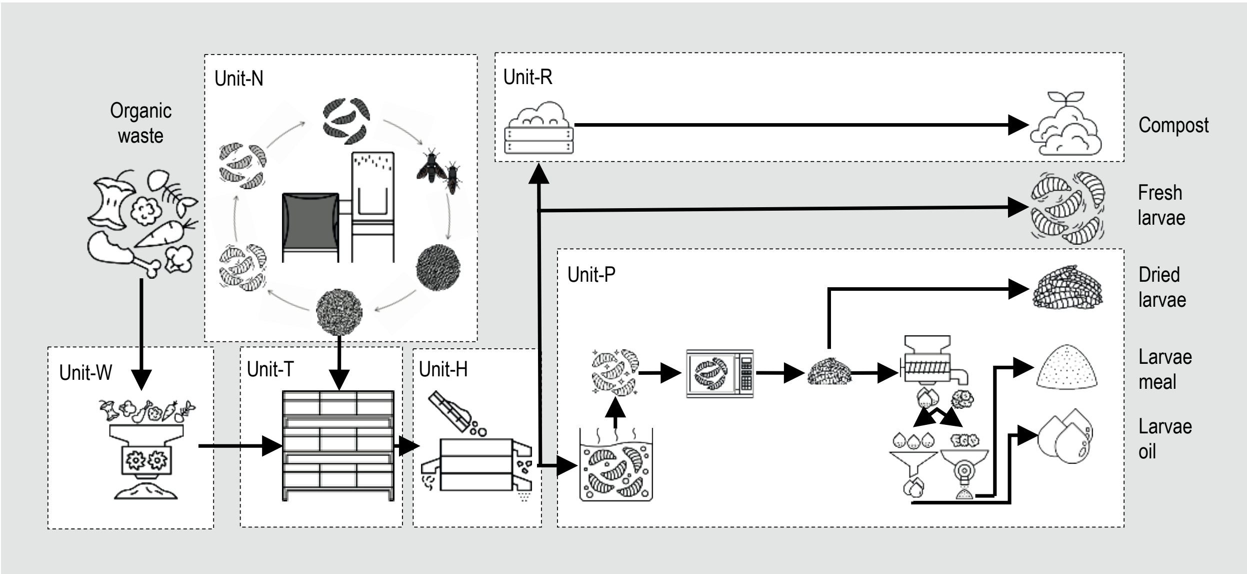

Figure 1. Black soldier fly larvae process overview; explanations of the various symbols in this graphic can be found in Supplementary Table S1.

unit. Here a first step is to sanitise and kill the larvae using boiling water, followed by a drying step. Although different drying technologies can be applied, (ovens, rotary driers or microwave ovens) this study accounted for microwave drying. The dried larvae can then be further processed to larvae meal and larvae oil using a screw press and a grinder. The separated waste in the harvesting step is called residue, which can be further processed to compost. Table 1 summarises the process steps at the pilot plant at Puspa Agro. Detailed equipment specifications for the complete process setup can be found in the supplementary data (Supplementary Table S2).

Table 1. Operational units of a black soldier fly larvae (BSFL) waste processing plant.

Name	Process	Description[1]
Unit-N	Nursery	Breeding of 5-DOL for input into Unit-T
Unit-W	Waste pre-processing	Pre-processing of raw organic waste
Unit-T	Waste treatment	Conversion of organic waste through addition of 5-DOL
Unit-H	Harvesting	Harvesting of 17-DOL and residue
Unit-P	Post processing	Processing of 17-DOL to BSFL products
Unit-R	Residue processing	Conversion of residue into compost

[1] DOL= day old larvae.

Scenario development

The six processing units are required to operate this setup of a BSFL waste processing facility and are typically combined in one plant. It is however also possible to separate different processing units as separate business units which can be placed at different geographic locations. Diener *et al.* (2015) described moving/relocating the rather simple waste treatment unit to decentralised locations while maintaining the more complex nursery unit and equipment intensive post-processing unit at a central location. This study models three different scenarios with various degrees of decentralisation (Figure 2, 3, 4), and described as separate business units, which interact with each other. Scenario 1 describes a setup of a centralised business that contains all processing units. In Scenario 2 only the nursery operation remains centralised, whereas the waste treatment and post-processing are decentralised at smaller plants in different locations throughout the city. Scenario 3, centralises the post-processing together with the nursery, leaving only the waste treatment units at decentralised locations.

In order to nourish the scenarios with real field data, the study relies on the composting site and transfer station of Wonorejo in Surabaya. At Wonorejo, a larger composting plant already exists with a maximum capacity of up to 20 ton/d. Based on this situation and discussion with local authorities, the study decided to model and analyse the scenarios based on a total organic waste processing capacity of 10 ton/d for BSFL waste processing. This was considered by the city authorities as a reasonable scale for further roll out of the BSFL waste processing approach.

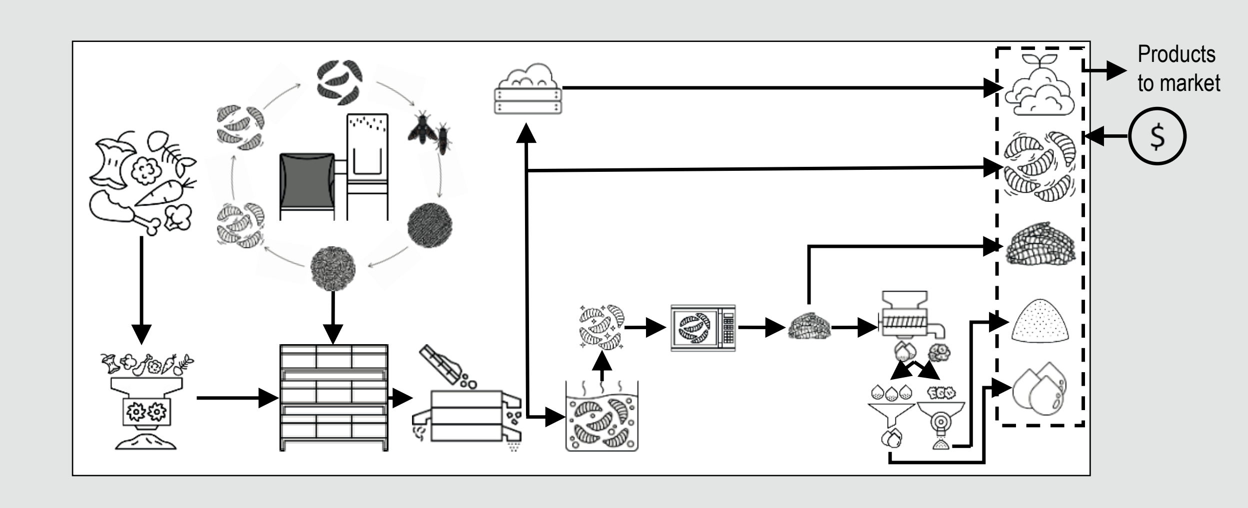

Figure 2. Scenario 1 (S1) with a centralised (C), integrated plant (S1C-WPN) consisting of all units (W = unit-W-T-H&R; P = unit-P; N = unit-N), selling all black soldier fly larvae products (fresh larvae, dried larvae, larvae meal and oil) on the market.

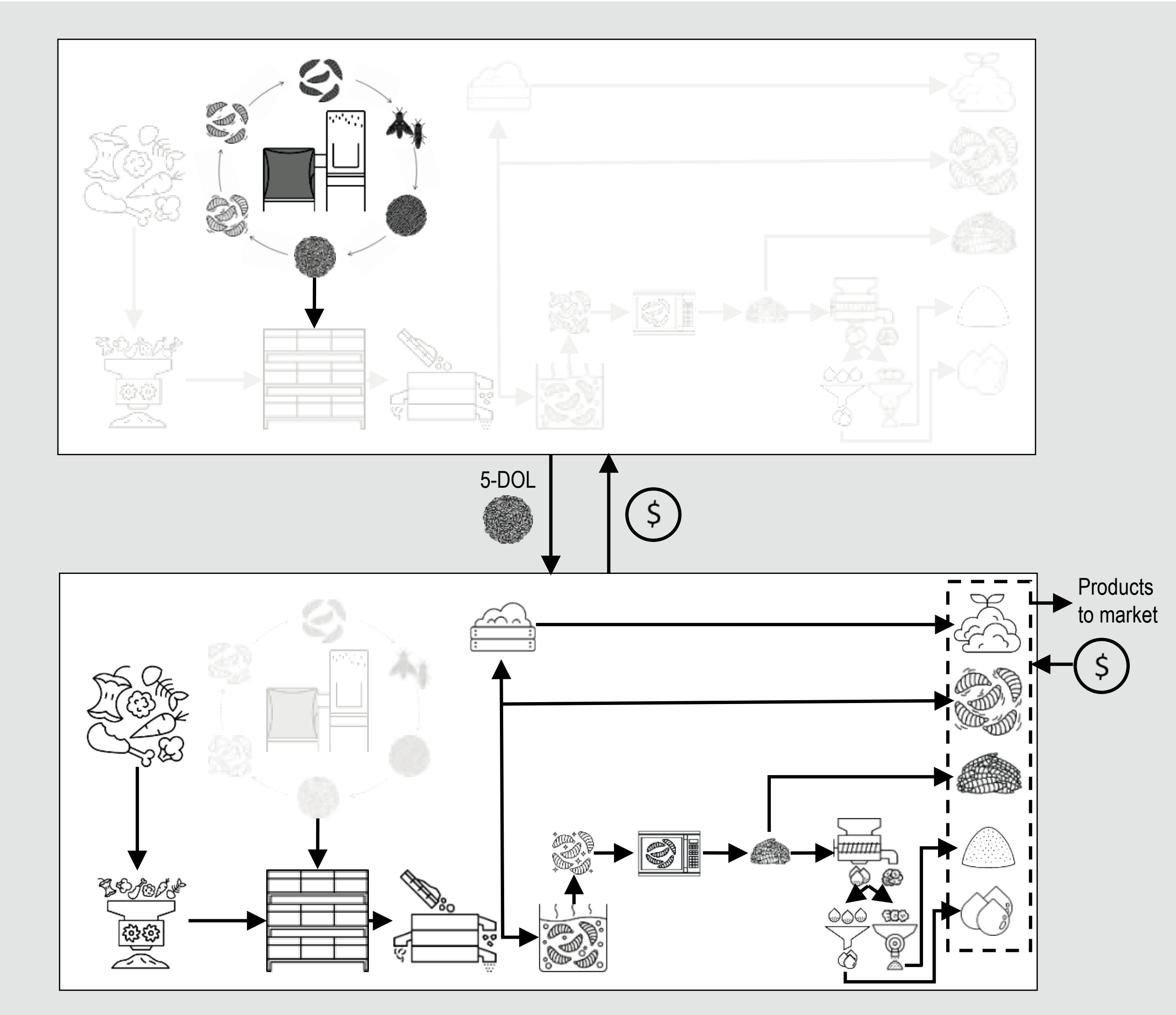

Figure 3. Scenario 2 (S2) with a centralised (C) unit (S2C-N) containing only the nursery (N = unit-N), supplying 5-DOL to a decentralised (D) plant (S2D-WP); S2D-WP contains the waste treatment and post-processing units (W = unit-W,T,H&R; P = unit-P) and sells black soldier fly larvae products (fresh larvae, dried larvae, larvae meal and oil) on the market.

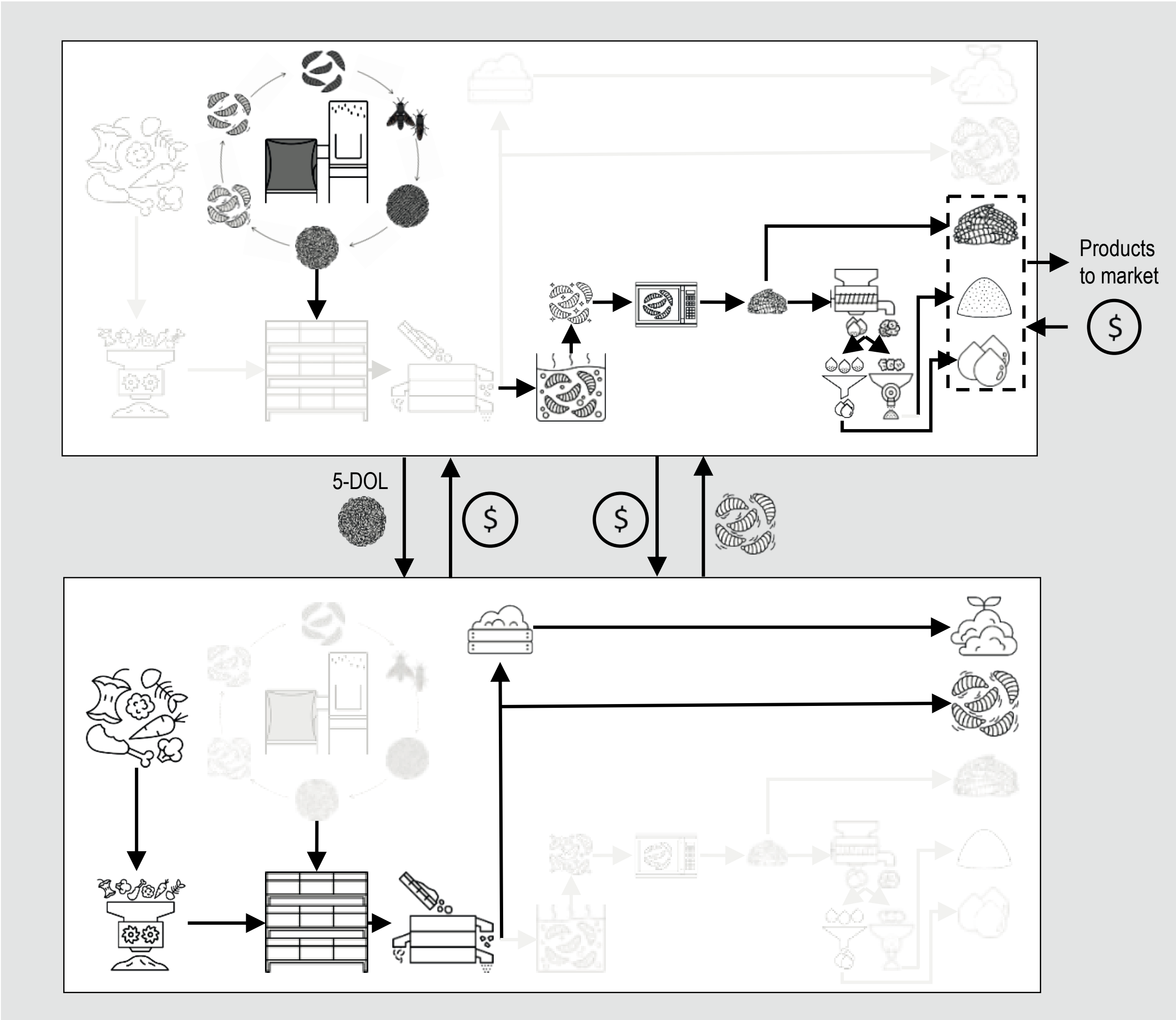

Figure 4. Scenario 3 (S3) consists of a centralised (C) nursery unit with post-processing (S3C-NP) and decentralised (D) waste treatment plants (S3D-W; W = unit-W,T,H&R); S3C-NP also sells black soldier fly larvae products (dried larvae, larvae meal and larvae oil) on the market whereas S3D-W sells fresh larvae to the centralised plant only.

The presented scenarios were analysed for their financial feasibility based on the Indonesian context. The basis for the financial evaluation is a BSFL plant, operated at Puspa Agro, in Sidoarjo nearby the city of Surabaya, Indonesia. The plant setup is described in Dortmans *et al.* (2021), using low cost mobile crates, nets and an approach that relies on manual labour and low-tech equipment where possible. The plant operates at a capacity of one ton fruit waste per day, from a nearby fruit and vegetable wholesale market. It has a designed capacity of up to 10 tons per day. Fresh and dried larvae, and larvae meal and oil are produced at this plant and sold.

Mass flow balance

A mass flow balance was established based on the activities at the plant. It quantifies the different in- and outputs at each process unit. Boundary conditions are the BSFL pilot plant operating with fruit waste that have total solids (TS) content of 3% on average. Given the multiple years of operating the plant, access to a large set of data measured was available regarding process parameters, which are included in the supplementary data (Supplementary Table S3). The nursery unit was also operated at the same site and monitored continuously to obtain the process parameters as included in the overview. All the values listed in the table are specific to the plant setup at Puspa Agro and the organic waste processed. The static mass flow model shows the possible production of various BSFL products (fresh larvae, dried larvae, larvae meal, larvae oil) and residue production based on the amount of incoming raw waste.

Capital costs

Equipment and infrastructure needed for the plant was itemised and the purchase costs added based on local rates (IDR), which were converted into USD (using a conversion rate of 14,122 IDR: 1 USD). The processing capacity was measured for each item. The equipment quantity required was calculated using the processing capacity per equipment and the amount of input to be processed. Installation and integration costs of the equipment were calculated using a factor of 2.5% of total equipment costs. The capital costs is the sum of all equipment costs, including the added factor for installation and integration. A list of the equipment used with capacities and respective capital costs can be found in the supplementary data (Supplementary Table S2). Required land and the factory building for the BSFL plant were rented, thus capital costs for these items were excluded.

Operating costs

Labour costs are the most dominant cost driver in this labour-intensive process setup. Labour time needed for various process steps was obtained through a time-motion study adapting the approach used by Dortmans (2015) using webcams with video analysis. Results are shown in Table 2 as labour time per kg output. This data was used to calculate the number of workers required per process step. Operating costs were further analysed using the activity based costing (ABC) method as described by Zurbrügg *et al.* (2018). The operating costs were categorised by material and labour costs needed for each step. Materials needed per process unit were measured as materials required per mass of output. Essential materials for the BSFL plant are coco peat, fruit water and compost, which are mostly used in the nursery unit. The waste pre-processing, treatment, harvesting and residue treatment units do not require additional material inputs. A list of materials and usage per processing unit can be found in Supplementary Table S4.

Additional labour costs, besides the labour costs captured in the time motion study in each unit, are costs for management and administration. Ratios were established, based on several years' experience at Puspa Agro, in order to estimate the number of additional staff needed (e.g. number of workers per manager). This can be found in Supplementary Table S5. Equipment maintenance costs were estimated at 5% of the total capital costs. Annual equipment depreciation costs were calculated using a straight-line method, splitting the equipment capital costs equally over the time of its useful life. No salvage value was assumed for the equipment, as no resell value was observed for the discarded equipment from the Puspa Agro plant. Utility costs were calculated based on utility usage of any equipment that requires water, electricity or fuel in units utilised per hour, multiplied by the total run time per day and the respective utility costs per unit. Rental costs were calculated per m^2 of floor space needed. The floor space for the BSFL plant was estimated using the equipment floor space, a space occupation factor, and an office space factor for office staff. The utility cost of the office space was estimated using an average electricity cost per office floor space at the Puspa Agro plant and the average water use per employee. Taxes and interests were not included in the operating costs. An overview list of inputs and their values for the model can be found in Supplementary Table S5. In the case of scenarios where different units are not located at the same location, coordinated transport is essential between units. Where the nursery is centralised and the waste treatment decentralised, 5-DOL need to be transported on a daily basis from the nursery to the treatment units (Scenario 2 and 3), and the harvested 17-DOL from the waste treatment units to the centralised plant

Table 2. Overview of results from time-motion study.[1]

Process unit	Step	Quantity	Unit
Unit-W	Sorting and shredding	0.003	h/kg pre-processed waste
Unit-T	Waste treatment with 5-DOL	0.010	h/kg 17-DOL + residue
Unit-H	Harvesting of 17-DOL	0.115	h/kg 17-DOL harvested
Unit-R	Residue to compost	0.025	h/kg residue
Unit-N	Production of eggs	287.0	h/kg egg
	Production of 5-DOL from eggs	1.0	h/kg 5-DOL
Unit-P	Sanitising 17-DOL	0.025	h/kg sanitised larvae
	Microwave drying sanitised larvae	0.049	h/kg dried larvae
	Screw pressing dried larvae for flakes and oil production	0.037	h/kg defatted flakes
	Grinding pressed larvae for meal production	0.030	h/kg larvae meal

[1] DOL = day old larvae.

for refining (Scenario 2). Transport costs were included using a simple transport model. The total transport of one round trip, i.e. from the centralised plant to each waste treatment unit and back to the centralised plant, is calculated using two parameters. The first parameter (D_1) describes the average distance from the centralised plant to the area of the waste treatment units and back. The second parameter (D_2) describes the average distance between a certain number of waste treatment units (x). The total distance (D_{total}) for one roundtrip is then calculated using Equation 1. Distances from the Wonorejo site to several existing transfer stations and MRFs in Surabaya were measured to obtain these parameters. All cost items included to calculate operating and capital costs of transport can be found in Supplementary Table S6.

$$D_{total} = 2 \times D_1 + (x-1) \times D_2 \qquad (1)$$

Revenue creation

A BSFL plant has several potential revenue streams. A gate fee per ton of waste of incoming organic waste for treatment is one possible source of revenue. However, as in the case of the plant at Puspa Agro, no gate fee for the fruit waste was charged. This revenue source was not included in any of the scenarios. Other revenue streams are from the produced and sold products, which are: (1) fresh larvae (FL), for sale to customers in close proximity; (2) dried larvae (DL); (3) defatted larvae meal (LM); and (4) crude larvae oil (LO). Production of LM always goes hand in hand with a production of LO given the process of defatting. A further product is the residue, which consists of residual organic waste and frass after harvesting of the grown larvae. This residue is further processed to compost.

Sale prices for each product category were determined according to the current market values of the products, derived from a market study realised for the Surabaya area. The target market studied was pet food, which shows higher potential prices than feed for farmed animals. Therefore, the prices shown in Table 3 may appear higher than values published in literature. Sales of compost was not considered as the Puspa Agro site gives compost away at no charge. Finally, 5-DOL from the nursery unit are sold as product to other BSFL waste treatment plants outside of the own business unit.

Financial metrics

An Excel-based model was developed to enter unit costs of labour, equipment and utilities as well as unit sale prices for different products. Based on the scale of operations selected, the model then provides results regarding the financial viability of a selected business model. To assess financial viability of each scenario, cash flow projections for several years were established. Discounting the cash flows with a selected discount rate, allows determination of the net present value (NPV). The NPV refers to the difference between the present values of all costs and potential revenues, calculated according to Equation 2. The NPV is the sum of all cash flows (CF) per year (n) for a designated time period (t), discounted at a discount rate (i) minus the initial capital costs (CC) to build the plant. The time period (t) was set at 5 years, representing the estimated maximum lifespan of equipment used in the plant. The discount rate (i) was set at 11%. A positive NPV indicates a viable business opportunity, whereas a negative NPV indicates that the business plan may not be financially viable. Internal rate of return (IRR) was calculated over the 5 year period using the internal Excel function.

$$NPV = \sum_{n=1}^{t} \frac{CF_n}{(1+i)^n} - CC \qquad (2)$$

Business unit and scenario analysis

Each business unit of the three scenarios was modelled with this above mentioned model, resulting in four distinct business models. In a first step the study analysed the various business units within each of the three scenarios. The aim was to understand if and under which conditions

Table 3. Overview of market prices for various products.[1]

Revenue stream	Description	Price per kg
Gate fee	Fee charged for treating organic waste	USD 0
Fresh larvae (FL)	Fresh larvae (17-DOL) for direct sales to customers in close proximity	USD 1.1
Dried larvae (DL)	Larvae after microwave drying	USD 7.8
Larvae meal (LM)	Pressed and grinded dried larvae, protein rich meal	USD 10.6
Larvae oil (LO)	Oil fraction after pressing dried larvae, rich in fatty acids	USD 9.9
5-DOL	5-DOL for waste treatment units	USD 53.1
Compost	Residue processed to compost	USD 0

[1] DOL = day old larvae.

each business unit can operate profitably, i.e. achieving a positive NPV. The prices for the various products (FL, DL, LM & LO) were kept constant as shown in Table 3. For the S1C-WNP unit, only the amount and type of product sold was modified. In business units of Scenario 2 and 3, 5-DOL and 17-DOL are exchanged between the central and decentralised units. In these cases, the prices of these two products are variable as they can be negotiated internally between the units, whereas the prices of the other BSFL product (FL, DL, LM & LO), as per Table 3, were kept constant as they are dictated by the external market value. The data table Excel function was used, to calculate multiple NPV values for a range of varying inputs, which resulted in creation of viability zones, within the NPV is greater than zero. Thereafter the results from the business unit analysis were used to define the input values for the scenario analysis to be within the viable zone for all units.

3. Results and discussion

Viability of the business units

The centralised plant – containing all processing and business units – in Scenario 1 was modelled at various scales to achieve a NPV break-even point or beyond. As shown in Figure 5, the smallest viable scale is at 2 ton/d organic waste treated, under the assumption that products LM & LO or a combination of DL with LM & LO (max. 60% DL) are produced and sold. Relying purely on sales of FL does not lead to viability at any scale given the current prices for FL and the cost of BSFL operations. With sales of 10% FL in the product mix combined with sales of DL, a scale of operations of 3.5 ton/d and above show to be financially viable. When selling FL combined with LM & LO, any plant size larger than 3.5 ton/d with sales of up to 20% FL is acceptable. These results show that post-processing of larvae to products of higher value improve the financial viability of a centralised plant and allows to operate viable plants at smaller capacities. The additional cost of post-processing is outweighed by the larger revenues from sales of the products. Although it might be attractive to sell FL given the lesser work involved, the percentage of FL sold should remain small to not compromise financial viability.

For Scenario 2, the business unit S2C-N only generates revenue by selling 5-DOL to the decentralised S2D-WP business unit. Minimum prices for 5-DOL can be calculated, to ensure viability of the S2C-N unit (Figure 6). When excluding transport costs, a 5-DOL price of at least USD 7 per kg will ensure viability when considering scale of production at 4 kg of 5-DOL per day or more. The price of USD 7 per kg of 5-DOL is almost 8 times lower than the current market price for 5-DOL at USD 53.1 per kg. When including transport costs at the same scale of production, the minimum price needed for 5-DOL increases from USD 10 to 15 depending on the transport setup. Smaller scales

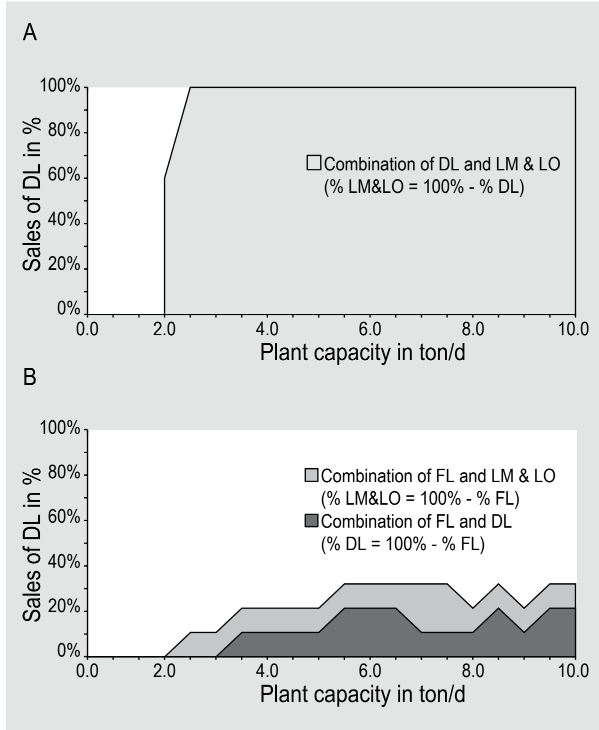

Figure 5. Scenario 1, centralised business unit S1A: (A) product sale combination of DL with LM & LO; (B) product sale combination of FL with DL or LM & LO. Shaded areas are zones of financial viability (NPV>0) based on plant waste treatment capacity (x-axis) and sales of different products (y-axis). DL = dried larvae; LM & LO = larvae meal and larvae oil; FL = fresh. Example: at 6 ton/d capacity and 25% sales of FL or DL, only the combination of FL with LM & LO is viable. Underlying data can be found in Supplementary Table S7.

and thus larger numbers of S2D-WP sites that have to be supplied with 5-DOL from S2C-N, has a larger effect on the viability of S2C-N than the distance between sites. At a price of USD 15 per kg 5-DOL, a production scale above 4 kg/d for the S2C-N units is viable, also when considering various transport setups, and these costs become negligible when the production scale is larger than 10 kg/d.

In Scenario 3, post-processing is combined with the nursery, forming the S3C-NP unit. Here the centralised S3C-NP unit sells 5-DOL, buys back 17-DOL and sells post-processed BSFL products. FL as product were not considered for S3C-NP, as the unit buys the 17-DOL from the decentralised sites at market price or higher, then selling the FL further as product at market rates would generate an immediate loss. Thus, only selling post-processed products (DL, LM & LO) makes economic sense. Calculations show that at acquisition cost of USD 1 per kg of 17-DOL, the S3C-NP unit can achieve viability even if 5-DOL are delivered without charge, under the precondition that 100% LM & LO is sold at a production scale of 3 kg 5-DOL per day or larger (Figure 7). Selling 100% DL increases the minimum viable

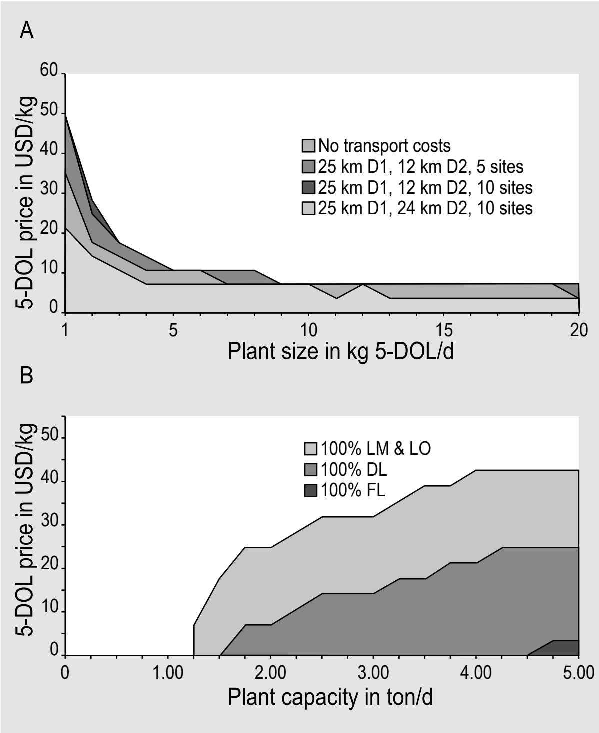

Figure 6. Scenario 2: (A) centralised business unit S2C-N. Shaded areas are zones of financial viability (NPV>0) based on 5-DOL production capacity of the plant (x-axis), sales price of 5-DOL (y-axis) and transport costs; (B) decentralised business unit S2D-WP. Zones of financial viability based on plant waste treatment capacity (x-axis), acquisition costs of 5-DOL (y-axis) and sales of different products. DL = dried larvae; LM & LO = larvae meal and larvae oil; FL = fresh larvae. Underlying data can be found in Supplementary Table S8 and S9.

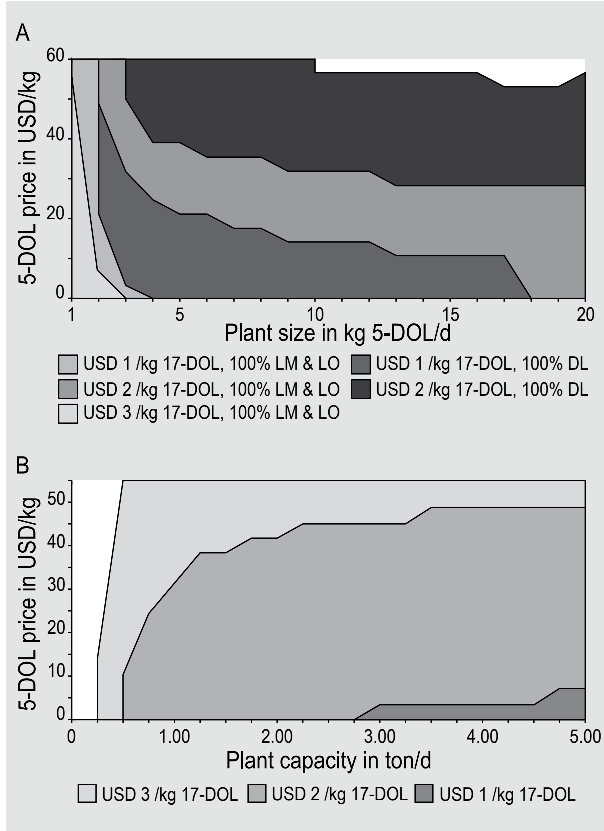

Figure 7. Scenario 3: (A) centralised business unit S3C-NP. Shaded areas are zones of financial viability based on plant 5-DOL production capacity (x-axis), sales price of 5-DOL, acquisition price of 17-DOL and sales of products; (B) decentralised business unit S3D-W. Zones of financial viability based on plant waste treatment capacity (x-axis), acquisition costs of 5-DOL (y-axis) and sales price of 17-DOL. Underlying data can be found in Supplementary Tables S10 and S11.

scale to 4 kg/d. If the acquisition costs for 17-DOL were to increase to USD 2 per kg, then minimum 5-DOL prices would have to increase drastically to maintain viability. With 100% LM & LO sales, a 5-DOL sales price of USD 20 per kg would be necessary at a production scale of 5 kg 5-DOL/d. At this same scale but selling 100% DL, would require a minimum sales price of USD 40 per kg 5-DOL. Such results show how critical the 17-DOL acquisition cost is for the S3C-NP unit. With an even higher acquisition cost of USD 3 per kg 17-DOL and 100% DL being sold, S3C-NP is not able to reach a positive NPV. If 100% LM & LO are sold at a 17-DOL acquisition costs of USD 3 per kg, then viability can only be achieved by increasing the scale of production beyond 10 kg 5-DOL/d and 5-DOL prices of USD 55 per kg, which is higher than current market rates. The results show, although selling additional BSFL products compared to the S2C-N unit allows very low prices for 5-DOL, that the S3C-NP unit is strongly dependent on the purchase price of 17-DOL from the S3D-W sites.

For Scenario 2 and 3, the decentralised units S2D-WP and S3D-W treat the organic waste, by obtaining 5-DOL from S2C-N or S3C-NP. They however differ in terms of products they sell. The S2D-WP unit can sell any BSFL product, but needs to consider the acquisition costs for the 5-DOL. The pricing of 5-DOL is thus crucial for the viability of the S2D-WP unit, as shown in Figure 6. The smallest viable S2D-WP unit can operate at a capacity of 1.25 ton waste/d when LM & LO are sold and the 5-DOL price is below USD 8 per kg. If selling 100% DL, a minimum operational waste treatment capacity of 1.75 ton/d is required with a maximum 5-DOL acquisition costs of USD 8 per kg. The current market rates for 5-DOL of USD 53.1 per kg are not affordable for the S2D-WP unit. Rather the maximum acquisition costs for 5-DOL is close to USD 45, if the waste treatment capacity of S2D-WP is larger than 4 ton/d and 100% LM & LO is sold. Selling 100% DL allows a maximum 5-DOL acquisition costs of USD 25 per kg, at waste treatment capacities larger than 4.25 ton/d. Selling 100% FL would drastically increase the minimum waste treatment capacity to 4.5 ton/d and above and only under the condition of a 5-DOL acquisition cost below USD 5 per kg. These results stress the importance of the need for an agreed pricing structure between the S2C-N and S2D-WP unit which operates outside of the current market rates, to create viability for both business units.

The S3D-W unit needs to purchase 5-DOL (Figure 7) and has the sale of 17-DOL as the only source of income. A sales price of USD 1 per kg 17-DOL, would need a minimum waste treatment capacity of 3 ton/d when considering an acquisition cost of less than USD 5 per kg 5-DOL. With a sales price of USD 2 per kg 17-DOL, the minimum waste treatment capacity shrinks to 0.5 ton/d under the condition of a maximum acquisition cost of USD 9 per kg 5-DOL. This low waste treatment capacity would be very favourable, as it allows a high degree of decentralisation of the waste treatment unit. However, this price for 17-DOL (i.e. fresh larvae (FL)) is almost double the current market price and creates significant business challenges for the S3C-NP unit as shown further above. If the waste treatment capacity were to be reduced even further to 0.25 ton/d, a pricing of USD 3 per kg 17-DOL would be required for viability. But at this price range for 17-DOL, the S3C-NP unit would not be able to bear the acquisition costs of 17-DOL without increasing the prices for 5-DOL, which again, the S3D-W unit could not afford. Results here also show that a price agreement outside market rates is required between the two business units S3C-NP and S3D-W if to achieve viability for both parties.

Scenario analysis

The results of the financial viability analysis show that selling FL reduces the chances of achieving a positive NPV, especially in the case of the S2D-WP unit. Selling FL is not an option for the S2C-NP unit. The benefits of higher value products through refining the fresh larvae outweighs the cost and efforts of the post-processing steps. Thus, a balanced product mix of 50% DL and 50% LM & LO, without selling FL, was chosen for the scenario analysis. The 17-DOL price was fixed at 2 USD per kg and 25 USD per kg for the 5-DOL to be within the viability zones for the units of Scenario 2 and 3. The distances to and between the decentralised sites were set according to the situation at Wonorejo. An overview of the set parameters is given in Table 4 and the results of the scenario analysis are shown in Table 5.

Table 4. Overview of set parameters for the scenario analysis to treat in total 10 tons of waste per day.[1]

Description	Unit/item	Value
Total waste to be treated	tons per day (t/d)	10
BSF product sales of total 17-DOL produced	% fresh larvae (FL)	0
	% dried larvae (DL)	50
	% larvae meal and larvae oil (LM & LO)	50
17-DOL pricing	USD per kg	2
5-DOL pricing	USD per kg	25
Transport costs	distance to sites (D1)	25 km
	distance between sites (D2)	10 km

[1] BSF = black soldier fly; DOL = day old larvae.

Table 5. Results of the scenario analysis.[1]

Scenario	1	2		3	
Unit	S1C-WNP	S2C-N	S2D-WP	S3C-NP	S3D-W
Number of plants	1	1	2	1	10
Plant capacity	10 ton/d	8.5 kg 5-DOL/d	5 ton/d	8.5 kg 5-DOL/d, 0.37 ton 17-DOL/d	1 ton/d
Plant size in m^2	1,544	51	741	129	168
Total staff	56	7	25	18	5
Capital costs (USD)	147,451	9,707	71,142	47,750	14,115
Operating costs (USD)	205,042	16,094	131,966	360,042	23,448
Internal rate of return	78%	628%	37%	35%	32%
Net present value (USD)	325,711	223,214	55,041	32,774	8,711

[1] DOL = day old larvae.

One centralised plant as per Scenario 1 (S1C-WNP), can be designed to treat the full 10 ton waste per day and can achieve financial viability. For Scenario 2, with a centralised nursery but decentralised waste treatment and post-processing of BSFL products, the results show that a minimum viable scale for the decentralised business unit (S2D-WP) should be at least 3 ton/d, based on a 50/50 product sales mix of DL and LM & LO and an acquisition price of 25 USD per kg 5-DOL. However, to match the required total treatment capacity of 10 ton/d, the capacity of S2D-WP was increased to 5 ton/d, resulting in two decentralised plants. For Scenario 3, where the decentralised units (S3D-W) perform only waste treatment, a S3D-W plant with a capacity of 1 ton/d lies within the viable zone. This setup would allow a decentralisation in 10 different waste treatment units dispersed across the city. For all scenarios – to treat 10 ton/d – the centralised unit needs to produce at least 8.5 kg 5-DOL per day in the nursery. A total of 374 kg of 17-DOL (fresh larvae) per day need to be refined to products either in the centralised unit (S3C-NP) or in the two decentralised units (S2D-WP). The highest NPV with around USD 325,000 is achieved for the centralised plant integrating all processing unit (S1C-WNP) in one plant. This achieves the highest level of economies of scale and best financial parameters. Decentralising the waste treatment achieves a NPV of roughly USD 55,000 for each decentralised S2D-WP site, that also processed larvae into products, and USD 8,700 for each decentralised waste treatment S3D-W site that doesn't process larvae. The centralised site with a nursery only (S2C-N) has a NPV of about USD 223,000 and including the processing of larvae products, decreases the NPV to USD 32,700. This indicates that when pursuing an approach towards partial decentralisation, it is best from a financial perspective to install a centralised nursery (S2C-N) only. This achieves an almost 20 times higher IRR of 628% compared to a situation of operating a nursery and a post-processing of BSFL products (IRR of 35%). Shifting waste processing and post-processing to decentralised units, would increase the IRR and NPV. However, this would require a larger minimum plant capacity of the decentralised unit thus reducing the total number of decentralised units.

Sensitivity analysis

A sensitivity analysis was conducted to investigate the influence of selected parameters on the financial viability. Parameters analysed were: discount rate for the NPV calculation, the product price for the various BSFL products (DL, LM & LO), the bioconversion rate (BCR) and the fuel prices. A change in BCR and product prices has the strongest impact on NPV followed by the discount rate (Figure 8). Not surprisingly, improving the bioconversion process to extract more larvae biomass from each unit of waste, increases the profitability of a BSFL business significantly, as also shown by Gold *et al.* (2020). Product prices and their fluctuations depend on the local market situation, but in general BSFL products do not yet benefit from an established market with reliable product prices. Particular attention needs to therefore be given to avoid under-pricing of BSFL products. In this business sector and its supply chain, collaboration and negotiations are required to ensure financial viability for all actors in the supply chain. An increase in fuel prices hardly affects the NPV, thus transport costs (e.g. fuel or distance) for transporting 5-DOL to decentralised sites and 17-DOL back to a centralised site play a minor role.

Transport of organic waste, space requirements and job opportunities

The results indicate that the best option in terms of NPV, IRR and robustness to changing product prices or process performance (BCR), is the centralised single unit. However, other factors besides financial viability may also influence decision-making of which approach to follow. While financial advantages for choosing a single centralised unit are shown in this study, other advantages and disadvantages of central versus decentral BSFL waste treatment have also been discussed by Diener *et al.* (2015). For the scenarios analysed, the transport of organic waste to the waste treatment unit was not included. Rahim *et al.* (2012) show that waste transportation costs are the largest cost component in the current solid waste management budgets of local authorities in Indonesia. This fact led to most municipalities installing decentralised collection and transfer stations and some even including recycling activities (MRFs) in each city district. A transfer station with a decentralised BSFL plant (S2D-WP or S3D-W) in proximity to the waste generators, reduces the need for long distance hauling after collection and also reduces the costs for larger distance transport to a disposal site or a central point including a S1C-WPN plant, as transporting untreated waste is a major cost contributor. In a decentralised approach the transport costs of 5-DOL or 5-DOL and 17-DOL show a minor impact on business viability, stressing the benefit of decentralising organic waste treatment. Recycling at decentralised locations in the communities also creates jobs within the communities. With decentralised sites at a capacity of 1 ton/d, each of the ten sites can create five jobs resulting in a total of 50 jobs for a total waste treatment capacity of 10 t/day. If larvae refining is included at the sites, this would generate jobs for 25 people at each of the two locations. Skills requirements for staff at a decentralised site treating waste is low, as described by Diener *et al.* (2015), thus allowing employment of people with limited educational background to create opportunities for the most vulnerable and fosters local and inclusive business models, as highlighted by Chia *et al.* (2019). In addition, decentralisation requires less space for many small plots (each 168 m^2) compared to one large plot for an integrated, centralised plant (1,544 m^2). This

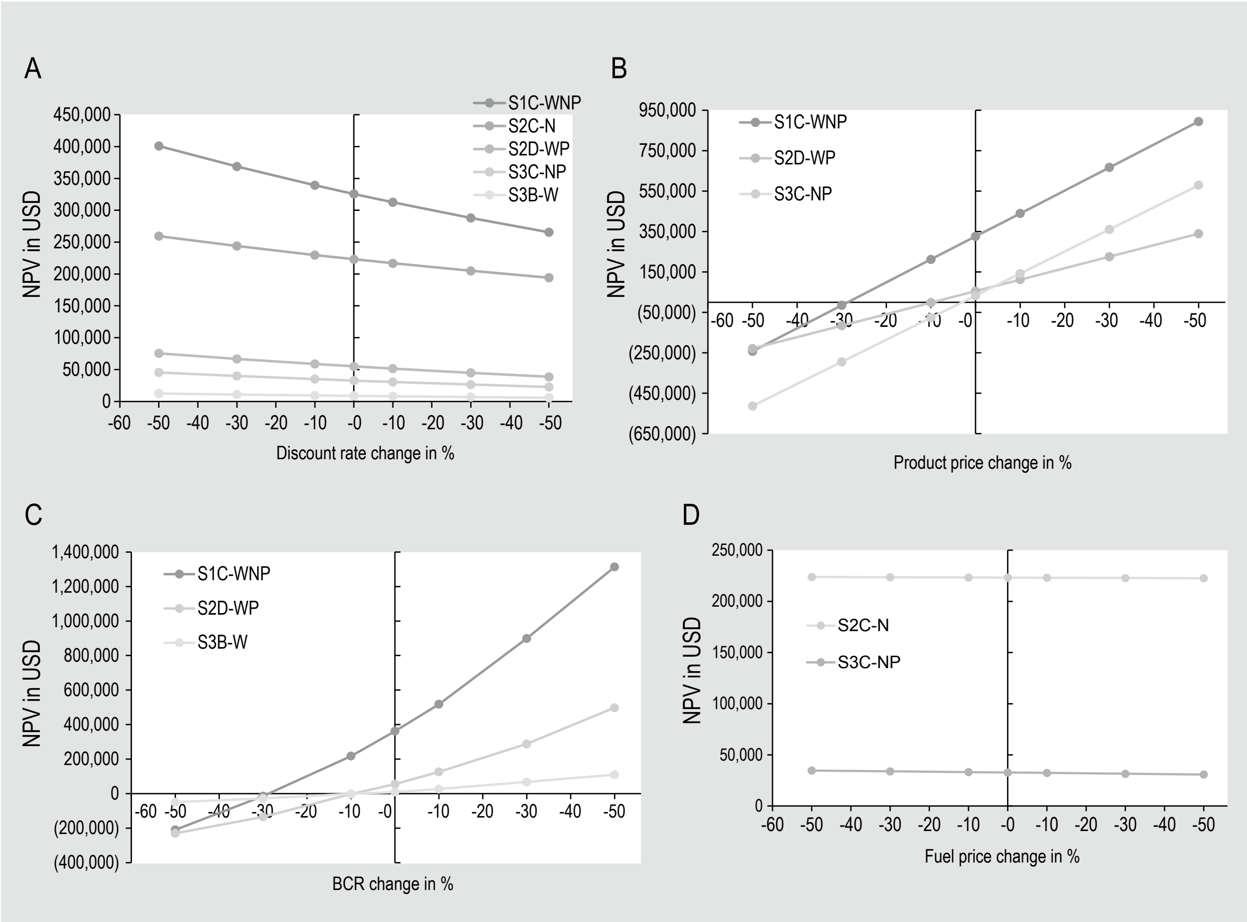

Figure 8. Impact of (A) change in discount rate, (B) product pricing, (C) biomass conversion rate (BCR) and (D) fuel price on the net present value (NPV) of the business units of the three scenarios; underlying data can be found in Supplementary Table S12.

could be advantageous, especially in the densely populated Surabaya region where finding a large plot of land is both very expensive and difficult, or else would only be available in large distance from the city. Although operating costs per ton increase with smaller units (Table 5), the required capital investment decreases. This allows small and medium businesses to establish more easily, whereas implementing a central unit would require a substantial amount of funding and a professional project development. A further advantage of decentralised units is that they can also processes the products (S2D-WP) which increases product quality and storability. The experience of waste banks in Indonesia has shown to improve waste separation, recycling and enhance the livelihoods within communities (Wulandari *et al.*, 2017), however these have yet not included organic waste processing.

Involvement of local government in black soldier fly larvae waste processing

Our study starts from the premise that BSFL plants are driven by private sector enterprises (formal or informal), thus we emphasise the need of financial viability and profitability of the various business units. However, the situation in Surabaya shows how a municipal authority may also spearhead innovative approaches in waste management, such as incentivising decentralised composting at household level (Gilby *et al.*, 2017). Surabaya has also taken a leading role in the development of BSFL treatment as one strategic step for its solid waste management master plan. Under such circumstances, new parameters can be introduced to study possible decentralisation of BSFL treatment units. For instance, the city could operate a central nursery and larvae refining centre at a non-profit level and thereby supply 5-DOL to decentralised waste treatment units at low or no cost. Ensuring an acquisition price of USD 2 per kg for 17-DOL from these decentralised units and an appropriate product sales mix, plant sizes for these decentralised units could be as small as 0.5 ton/d and still be profitable. Benefits for the city would be: (a) financial, regarding costs savings in transport of untreated waste; (b) societal, by generating jobs in the communities, and (c) environmental, by reducing greenhouse gas emissions through reduced transport and disposal.

4. Conclusions

A combination of a static mass flow balance, time motion studies and the ABC method led to the creation of a comprehensive business model for an existing BSFL plant. Structuring it according to the processing units made it possible to adapt the model to various scenarios successfully. Given the results presented, we argue that using a decentralised waste treatment unit with post-processing of the larvae (S2D-WP) might be more beneficial from a holistic perspective. If 5-DOL can be supplied by the public waste management services at low or no costs, small units of 1.25 ton/d can be built and operated viably, still achieving a higher degree of decentralisation. Modifying the drying technique from a capital intensive microwave (as used in this study), to other means of drying (e.g. pan drying, rotary drier) and not processing the larvae further to larvae meal and oil, will potentially even further reduce the smallest viable scale, due to saved capital and operating costs. Creating higher value products, such as dried larvae, at the decentralised sites, allows the business owner to achieve a higher income while not being dependent on a buy-back scheme for 17-DOL. The produced products also have an extended storability, minimising risk of product loss. This study demonstrated the viability of decentralising BSFL treatment in the Indonesian context, specifically in Surabaya. Being able to conduct a business analysis paves the way to set up a structure for a potential decentralised system at current transfer stations or MRFs in Surabaya. Viable and inclusive business models can be created using the BSFL conversion process, while achieving the waste reduction and recycling goals together with a sustainable community development. The business model tool developed for this study can also support the city as a planning tool to decide on viable plant sizes and pricing structures for 5-DOL and 17-DOL to study the potential options for decentralised organic waste treatment using BSFL.

Supplementary material

Supplementary material can be found online at https://doi.org/10.3920/JIFF2022.0012

Table S1. Symbols and descriptions.

Table S2. Equipment specifications.

Table S3. Black soldier fly larvae process parameters.

Table S4. Materials used.

Table S5. Model input data.

Table S6. Transport costs input data.

Table S7. NPV values for S1A unit for various product compositions and scales.

Table S8. NPV values for S1A unit for various product compositions and scales.

Table S8. NPV values for S2A unit for various 5-DOL prices, transport setups and scales.

Table S9. NPV values for S2B unit for various 5-DOL prices, transport setups and scales.

Table S10. NPV values for S3A unit for various 5-DOL prices, 17-DOL prices, scales and products sold (incl. transport costs only).

Table S11. NPV values for S3B unit for various 5-DOL prices, 17-DOL prices, and scales.

Table S12. Sensitivity analysis – NPV values for the three scenarios depending on changes of selected parameters.

Acknowledgements

This work was supported by the project teams of FORWARD and SIBRE. The FORWARD project operated in collaboration with the Indonesian Ministry of Public Works and was funded by the Swiss State Secretariat of Economics Affairs (SECO) [grant number UR-00482.01.01]. The SIBRE project was funded by the Swiss Re Foundation [grant number 6361]. We would like to thank especially Putu Putri Indira Sari and Early Antarest for helping with the data collection at the pilot plant in Puspa Agro, Sidoarjo.

Conflict of interest

The authors declare no conflict of interest.

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