Development of optimisation model for black soldier fly-based aquaculture feed supply chains in Malaysia

C A Ng, C W Chan, V Andiappan, L Y Ng and D K S Ng

1 School of Engineering and Physical Sciences, Heriot-Watt University Malaysia, 62200, Putrajaya, Wilayah Persekutuan Putrajaya, Malaysia
2 Agridon Technologies, Lot 2745-D, Jalan Industri 12, 47000 Kampung Baru Sungai Buloh

Email: Denny.Ng@hw.ac.uk

Abstract. Aquaculture is identified as one of the critical food supplies in Malaysia. Due to the increasing demand for aquaculture products, the demand for protein sources for fish feed is also increased accordingly. Black soldier fly larvae is identified as one of the main protein sources that can be used in fish feed. Such larvae can be grown using different types of organic materials, such as food waste, agriculture waste, etc. As Malaysia is the second-largest palm oil producer in the world, therefore, a large number of agricultural wastes, also known as palm-based biomass (e.g., empty fruit bunches, mesocarp fibre, decanter cake, etc.) are generated annually. Based on the current industry practise, palm-based biomass can be converted into value-added products. However, using palm-based biomass as feedback to grow black soldier fly larvae is a relatively recent discovery. Thus, a viable supply chain model has yet to be established. In this work, a mathematical optimisation model is developed via commercial optimisation software (Lingo v.16) to synthesise an optimum black soldier fly-based aquaculture feed supply chain that utilised palm–based biomass as the feedstock. Based on the optimised result, the annual operating cost of the aquaculture feed supply chain is estimated as RM 5.2 million.

1. Introduction
The aquaculture industry involves cultivation of aquatic lifeforms for sustenance and food source. In Malaysia, the aquaculture industry has been identified as a critical food supply since the 7th Malaysia Plan [1]. As the population of Malaysia increases, it is estimated that the demand for fish will also increase. From 1983 to 2019, the production of aquaculture products has increased from 44,000 tonnes per annum to 220,000 tonnes per annum [1].

In Malaysia, brackish water fish culture, freshwater fish culture, and marine fish culture are the common type of aquaculture system. Brackish water fish culture is aquaculture farms that are built on water with salinity between freshwater and seawater; freshwater fish water culture is aquaculture farms that are built on freshwaters such as river and lake; and marine fish culture are aquaculture farms that are built offshore. Note that brackish water fish culture is the dominant practice in Malaysia, with 70 % of the aquaculture farms in Malaysia [1]. Besides, freshwater and marine aquaculture encompass the remaining 30 %. Cobia fish is the most common fish that rears in brackish fish culture [1]. Since Cobia fish are carnivorous, the feed must have sufficient digestible materials [2].

According to the literature [3], larvae from larvae of black soldier fly (Hermatia illucens) can be used as a raw material to produce fish feed for carnivorous fish. Black soldier fly is a type of fly in the
Hermatia genus. The average size of this fly larvae is approximate 24 mm long and 8 mm wide. The life cycle of a black soldier fly last approximate 45 days: Eggs (4 days), Larvae stage (18 days), Pupae stage (14 days), and adult stage (9 days) [4]. Note that the larva is suitable to be used as fish feed because of the high nutrient and protein contents (16 %), as shown in table 1.

Table 1. Proximate analysis of black soldier fly larvae [5].

| Parameters    | % dry weight |
|---------------|-------------|
| Moisture      | 62.0        |
| Lipids        | 7.0         |
| Protein       | 16.0        |
| Ash           | 3.0         |
| Crude Fibre   | 3.0         |
| Carbohydrate  | 9.0         |

Note that black soldier fly larvae contain a high level of protein which is important to enhance the health of the fish. Black soldier fly larvae grow well in agricultural wastes such as rotten vegetables, spent rice grains and palm-based biomass [6]. Therefore, growing larvae via palm-based biomass can be used as a strategy for sustainable waste management.

Palm oil products is ranked the top ten Malaysia’s export goods [7]. In 2020, Malaysia exported 17.3 million tonnes of palm oil products [7]. Therefore, it is important to ensure a sustainable production of palm oil products. During the extraction of crude palm oil from fresh fruit bunches, various types of palm-based biomass such as empty fruit bunches, palm kernel cake, decanter cake, palm oil mill effluent, etc. are produced [8] Due to the large quantity of biomass being produced from palm oil mills, various technologies have been developed to convert palm-based biomass into value-added products [9]. For example, empty fruit bunches and palm kernel shell are used as fuel in the boilers to generate steam and electricity [10], whereas palm kernel cake can be used as animal feeds [11].

As the demand of fish feed increased, such palm-based biomass can be used as raw material for breeding black soldier fly for larvae production [12]. Palm-based biomass such as palm kernel cake is suitable to be used as food for black soldier fly larvae as it consists of sufficient protein content that is needed for insect rearing [13]. In order to sustainable production of black soldier fly larvae as aquaculture feed, an aquaculture supply chain needs to be developed. Such supply chain is a complex network of material flow through the aquaculture industry that involves different materials such as aquaculture feed, fish egg, fish products and intermediate products. Due to the complexity of the entire aquaculture supply chain, the aquaculture supply chain can be subcategorised into multiple sections which are aquaculture feed production supply chain, fish farm management supply chain and end-user fish product supply chain. In this work, aquaculture feed production supply chain is to be analysed.

To optimise the aquaculture feed supply chain, a mathematical model needs to be developed. However, there are limited research works focus on aquaculture supply chain optimisation. Aquaculture supply chain optimisation covers the optimisation of configuration and material flow network in the aquaculture supply to maximise profitability, minimise operating cost and maximise the productivity in the aquaculture supply. Gagalyuk et al. [14] presented a supply chain network for the fish supply chain to maximise the profitability of fish retailers in Germany and tested its validity empirically using Partial Least Squares Structural Equation Modelling based on surveys from fish retailers in Germany. Bakhrankova et al. [15] developed an integral stochastic model that includes raw material supplies and downstream product flow to improve capacity utilisation, operational efficiency, and profitability. Bakhrankova et al. [15] also accounted for fish quality deterioration and shelf life restrictions when developing the model. Malindretos et al. [16] used value stream mapping methodology to improve cost savings and lead time from production to consumption of fish in Greece. Abedi and Zhu [17] used mixed-integer linear programming (MILP) to optimise the production of trout farm based on spawn.
purchase quantity, the best time to harvest and the farming period. Table 2 summarises the optimisation objective of the previous works.

### Table 2. Summary of literature involving aquaculture supply chain optimisation.

| Literature                  | Optimisation objective                              |
|-----------------------------|-----------------------------------------------------|
| Gagalyuk et al. (2010)      | Maximise the profitability of fish retailers in Germany |
| Bakhrankova et al. (2014)   | Maximise capacity utilisation, operational efficiency and profitability. |
| Malindretos et al. (2016)   | Minimum lead time from production to consumption of fish |
| Abedi and Zhu (2017)        | Maximum profitability of trout sold                 |

It is noted that the above mentioned works [14–17] are focusing on maximising the profitability of the end-user aquaculture products. Those works do not consider the cost of aquaculture feed in their approaches when optimising the aquaculture feed supply chain. As shown in literatures [14–17], the previous works focused mainly on the supply chain downstream from the aquaculture fish farm such as the production efficiency of aquaculture farms, the benefits of different aquaculture farms cooperating and the flow of product from fish retailers to consumers. Limited works are presented to optimise the upstream of aquaculture fish farms such as minimising the cost of fish feed to aquaculture farm. Furthermore, none of the work utilises palm-based biomass as feed in an aquaculture feed supply chain. Therefore, this work aims to integrate palm-based biomass into the development of aquaculture feed supply chain that produce fish feed via bioconversion of black soldier larvae.

As reported in the previous works [12,18,19], different agricultural wastes have been used to grow black soldier fly larvae. Leong et al. [18] analysed the proximate analysis of black soldier fly larvae fed with sewage sludge, palm decanter and fruit waste. Bokau and Witoko [12] presented the effect of probiotics concentration mixed with palm kernel cake towards crude protein content in the black soldier fly larvae. Mujahid et al. [19] analysed the growth rate of black soldier fly larvae fed with empty fruit bunches.

Based on the literature information, a mathematical optimisation model of an aquaculture feed supply chain that product fish feed from black soldier fly larvae is developed in this work. In this supply chain, source of palm-based biomass, quality of the biomass, location of the black soldier fly farm and operating cost of production are considered.

### 2. Problem Statement

A superstructure of the aquaculture feed supply chain is first developed in this work. Given palm-based biomass $k \in K$ (Palm kernel cake, palm oil mill effluent, empty fruit bunch etc.) are collected from palm oil mills $i \in I$ and then be transported to black soldier fly farm $j \in J$ using transportation modes $z \in Z$. For cases where black soldier fly farm $j$ located in palm oil mill $i$, the distance will be given as 0. The mathematical model also considers the possibility of separating black soldier fly rearing processes and feed processing facilities into different locations. For cases where black soldier fly farm and feed processing facilities are located together, the distance will be given as 0. In the black soldier fly farm $j \in J$, processing technologies $w \in W$ are employed to convert palm-based biomass $k$ into suitable composition for bioconversion into black soldier fly larvae. Black soldier fly larvae are then further processed into fish feed using various processing technologies $w' \in W'$. Technologies considered in the intermediate stages are processes such as drying, pelleting and pre-treatment process. The final fish feed is then transported to the port $l \in L$ via transportation modes $z' \in Z'$. Figure 1 illustrates the superstructure aquaculture feed supply chain.
3. Mathematical Formulation

To synthesize an optimum aquaculture feed supply chain with minimum operating cost, the following mathematical model, which presented in the following sub-sections, is formulated using the commercial optimisation software.

3.1. Material Balance

Based on the superstructure in figure 1, the availability of biomass $k$ per batch ($F_{k, \text{biomass,batch}}$) is given in this work. The distribution of palm-based biomass $k$ from palm oil mills $i$ to farm $j$ per batch ($F_{k,j, \text{biomass,batch}}$) can be determined via equation (1).

$$F_{k,j, \text{biomass,batch}} = \sum_{i=1}^{I} F_{i,j,k, \text{biomass, batch}} \quad \forall j, \forall k$$

The production of larvae per batch from biomass $k$ ($F_{k,j, \text{larvae,batch}}$) can be determined based on the given conversion of biomass $k$ to larvae, $X_{k, \text{larvae}}$.

$$F_{k,j, \text{larvae,batch}} = F_{k,j, \text{biomass,batch}} X_{k, \text{larvae}} \quad \forall j, \forall k$$

To convert the production of larvae from per batch basis to annual basis, $F_{k,j, \text{larvae}}$. Production of larvae per annum from biomass $k$ ($F_{k,j, \text{larvae}}$) can be determined by the number of larvae batches produced from biomass $k$ per annum, $n_{k,j, \text{batch}}$.

$$F_{k,j, \text{larvae}} = F_{k,j, \text{larvae,batch}} n_{k,j, \text{batch}} \quad \forall j, \forall k$$

As larvae growing is a batch process, different biomass requires a different amount of time $t_{k, \text{batch}}$ to grow the larvae. Therefore, $F_{k,j, \text{larvae}}$ must not exceed the maximum amount of larvae that can be produced using biomass $k$ $F_{k,j, \text{max,larvae}}$ as shown in equation (5). $F_{k,j, \text{max,larvae}}$ is determined using equation (6).

$$F_{k,j, \text{larvae}} \leq F_{k,j, \text{max,larvae}} \quad \forall j, \forall k$$
\[ F_{k,j}^{\text{larvae, batch}} = \sum_{i=1}^{K} F_{k,j}^{\text{biomass, batch}} \times n_{k,j}^{\text{batch}} \quad \forall j, \forall k \] (6)

where \( t_{\text{max}} \) is the maximum available time to produce the larvae per year. The output of larvae from farm \( j \) \( F_{j}^{\text{larvae}} \) is the summation of larvae output from each biomass \( k \). Besides, the mass of dried larvae is the mass of larvae \( F_{j}^{\text{larvae}} \) multiplied with dry fraction.

\[ F_{j}^{\text{larvae}} = \sum_{k=1}^{K} F_{k,j}^{\text{larvae}} \quad \forall j \] (7)

\[ F_{j}^{\text{dried}} = (1 - \text{moisture}) F_{j}^{\text{larvae}} \quad \forall j \] (8)

### 3.2. Operating Cost Modelling

For the operating cost modelling, it is categorised into three different costs, mainly biomass purchasing cost \( C_{j}^{\text{biomass}} \), intermediate processing costs \( C_{j}^{\text{process}} \) and transport cost \( C_{j}^{\text{transport}} \). The biomass cost is modelled as the summation of the flowrate of each biomass \( k \) to farm \( j \) multiplied by the cost of biomass, \( C_{k} \), respectively.

\[ C_{j}^{\text{biomass}} = \sum_{k=1}^{K} C_{k,j}^{\text{biomass}} F_{k,j}^{\text{biomass, batch}} \quad \forall j \] (9)

The intermediate processing costs \( C_{j}^{\text{process}} \) is the cost of converting palm based biomass into the final product, fish feed. Hence, it is the cost summation of each processing step as shown in equation (10) below.

\[ C_{j}^{\text{process}} = \sum_{k=1}^{K} \sum_{w=1}^{W} \left( F_{k,j}^{\text{biomass}} C_{w} \right) + \sum_{k=1}^{K} \sum_{w=1}^{W'} \left( F_{k,j}^{\text{larvae}} C_{w'} \right) \quad \forall j \] (10)

The cost of transport \( C_{j}^{\text{transport}} \) is the cost summation of all transportation cost which includes transporting biomass from palm oil mill \( i \) to black soldier fly farm \( j \) as well as transporting final feed product from black soldier fly farm \( j \) to port \( l \) as shown in equation (11) below.

\[ C_{j}^{\text{transport}} = \sum_{i=1}^{I} \sum_{k=1}^{K} \sum_{z=1}^{Z} \left( D_{i,j,k} \times C_{z,j} \right) + \sum_{l=1}^{L} \sum_{z'=1}^{Z'} \left( D_{l,j} \times C_{z' \text{dried}, l} \right) \quad \forall j \] (11)

The mass transport of biomass from palm oil mill \( i \) to black soldier fly farm \( j \), \( D_{i,j,k} \), is the product of mass flowrate of biomass \( k \) from palm oil mill \( i \) to black soldier fly farm \( j \), \( F_{i,j,k} \), and the distance between farm \( j \) and palm oil mill \( i \), \( D_{i,j} \). The distance between the farm \( j \) and palm oil mill \( i \) was calculated by inputting the coordinates of farm \( j \) and palm oil mill \( i \) into Google Maps then determining the shortest road distance between the 2 locations.

\[ D_{i,j,k} = F_{i,j,k} \times D_{i,j} \] (12)

\[ F_{i,j,k} = \sum_{l=1}^{L} \left( F_{i,j,k}^{\text{biomass, batch}} \times n_{k,j}^{\text{batch}} \right) \quad \forall j, \forall k \] (13)

The mass transport of final feed product from black soldier fly farm \( j \) to port \( l \), \( D_{l,j} \), is the product of mass flowrate of final feed product from farm \( j \) to port \( l \), \( F_{l,j}^{\text{dried}} \), and the distance between farm \( j \) and port \( l \), \( D_{l,j} \). The distance between the farm \( j \) and port \( l \) was also calculated by inputting the coordinates of farm \( j \) and port \( l \) into Google Maps then determining the shortest road distance between the 2 locations.

\[ D_{l,j} = F_{l,j}^{\text{dried}} \times D_{l,j} \] (14)

The operating cost at each farm in the supply chain is thus the sum of all the different costs at each farm.

\[ C_{j}^{\text{total}} = C_{j}^{\text{biomass}} + C_{j}^{\text{process}} + C_{j}^{\text{transport}} \quad \forall j \] (15)

The objective function of this mathematical model is to minimise the operating cost \( C_{j}^{\text{total}} \). Hence the objective function is given as in equation (16).

\[ \text{Minimise } C_{j}^{\text{total}} \] (16)
4. Case Study

In this supply chain optimisation approach, the objective function is to minimise operating cost $C_{\text{total}}$. In this case study, three Black Soldier Fly (BSF) farms operate to produce 1200 tonnes of pelletised feed per annum in each farm. To convert the biomass into larvae then aquaculture feed, the supply chain will have to go through several unit operations which are pre-treatment, bioconversion, drying and pelletisation. Each process has several technologies that can be applied; thus the selection of technology was considered by the model based on each technology’s operating cost. On the other hand, the protein content of the larvae produced was not constrained in this case study.

With the data collected, a mathematical model of the superstructure was developed using LINGO 18.0. The target feed production output was set as 1200 tonnes per annum. This is because a typical black soldier fly farm produces 150 kg per hour and operates 8000 hours per annum (20). The mathematical model was solved with the constraints in mind and the feed production configuration per batch of BSF larvae is illustrated in figure 2 while the optimised supply chain is illustrated in figure 3.

Figure 2 shows that the pre-treatment technology selected is aerobic digestion as the cost of aerobic digestion is lower. The drying technology selected is rotary drying as it has the lowest operating cost. Moreover, the pelletisation technology chosen is the pelletiser rather than single screw extrusion. This is because the pelletiser operating cost is lower than the single screw extrusion.

Figure 3 shows that Palm Oil Mill (POM) i2, i3 and i7 is selected to supply the biomass to Farm j2, j1, and j3 respectively. This is because the distance is the shortest between i2 to j2, i3 to j1 and i7 to j3. Besides, that the biomass selected is only Empty Fruit Bunches (EFB). This is because the EFB bioconversion rate is the highest and thus less EFB is needed to be fed to the larvae. Furthermore, the price of EFB is the lowest at RM 32 per ton. Thus, EFB is selected as the biomass in the model. The biomass was then transported using the 10 tons truck. Although the 10 tons truck cost more per kilometre transported, the truck’s capacity is higher therefore a smaller number of trips between the farm and the mill is needed. Furthermore, feed produced from farm j1 and j2 is transported to Port Klang for storage and feed produced from farm j3 is transported to Port Dickson for storage. This is because farm j1 and j2 are closer to Port Klang and farm j3 is closer to Port Dickson.

![Figure 2. Optimised feed production configuration.](image-url)
Additionally, it is noted that the model decided against separating the black soldier fly farm from the feed processing facilities. This is because it would cost more to transport the larvae to a separate facility to process larvae into feed thus it would increase the transport cost and operating cost. The operating cost of each BSF farm is illustrated in table 3. Overall, the operating cost is RM 5.2 million per annum for BSF farm j1, RM 5.3 million per annum for BSF farm j2 and RM 5.4 million per annum for BSF farm j3. The difference in the operating cost is attributed to the transportation cost to transport biomass to the farm and to transport the pelletised feed to the port.

Figure 3. Optimised feed production superstructure.
Table 3. Optimised BSF feed production cost.

|                          | BSF Farm $j_1$ (RM/year) | BSF Farm $j_2$ (RM/year) | BSF Farm $j_3$ (RM/year) |
|--------------------------|---------------------------|---------------------------|---------------------------|
| Biomass Cost, $C^{\text{biomass}}$ | RM 265,000                | RM 265,000                | RM 265,000                |
| Process Cost, $C^{\text{process}}$ | RM 4,871,000              | RM 4,871,000              | RM 4,871,000              |
| Transport Cost, $C^{\text{transport}}$ | RM 63,000                 | RM 159,000                | RM 277,000                |
| Total Operating Cost, $C^{\text{total}}$ | RM 5,200,000              | RM 5,300,000              | RM 5,400,000              |
| Larvae crude protein content (% wt) | 13.49                     | 13.49                     | 13.49                     |

5. Conclusion

In conclusion, a mathematical model for the aquaculture feed supply chain is synthesised in this work. The developed mathematical model considers the mass balance of the supply chain, distance between palm oil mill and black soldier fly farm, protein content of the biomass, bioconversion rate and technology cost when selecting the biomass and technology. The optimised model shows that the optimised feed production cost is lower compared to commercial feed prices and thus the results show that it is more cost-effective for aquaculture companies to manufacture feed compared to purchasing commercial feeds in the market. Future works that can be done to improve the model is to introduce the GHG emissions of each unit operations as a constraint for the model to consider in the technology and biomass selection for each unit operations. Besides, the capital cost of setting up the feed manufacturing process was not considered and can be a prospect for future works. It can be noted that the variability of biomass prices, biomass quality and technology cost can be easily updated and remodelled based on updated data.

Acknowledgments

The authors are grateful to the School of Engineering and Physical Science, Heriot-Watt University Malaysia and Triple Vs Venture for supporting this research work. The contributions of Bluestream Mariculture Sdn Bhd for sharing data on the aquaculture feed supply chain is also acknowledged and appreciated.

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