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# Opportunities, challenges and solutions for black soldier fly larvae-based animal feed production

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A R T I C L E I N F O

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A B S T R A C T

Increasing global demand for animal protein combined with an urgent need to advance towards global sustainability, as enshrined within the Sustainable Development Goals (SDGs), has spurred the development of insects as a protein source in animal and fish feed. The acceptance and feasibility of these advances are nevertheless poorly understood. This study aimed to identify opportunities, challenges and solutions for black soldier fly larvae-based animal feed production, through stakeholder interviews in Malaysia, analysed using thematic analysis and the analytic hierarchy process. The data identified 17 challenges, alongside 19 potential solutions, which we analysed under political, economic and resourcing, institutional and legal, and social and cultural categories. The need to establish a black soldier fly larvae-based feed sector has become important, but for black soldier fly larvae feed to make a substantive contribution to the animal feed sector, a more enabling environment is required. This includes improved support from the government, ensuring cost-effective investment and low operational costs, better coordination between regulatory authorities and improved consumer acceptance. Tackling these challenges from multiple entry points within each of the categories we identified could help to advance policies that advance progress towards the SDGs through the development of black soldier fly larvae-based animal feed production, supported by the engagement of multiple stakeholders. Policy recommendations emerging from this study offer important inputs to inform black soldier fly larvae-based animal feed production both in Malaysia and globally.

## 1. Introduction

Unsustainable production and consumption are associated with global environmental challenges including climate change (Vermeulen et al., 2012), biodiversity loss and land use change (Newbold et al., 2015), water insecurity (challenges in obtaining a secure water supply in relation to aspects of stability (regular supply), quality, availability and accessibility) (Wada et al., 2010), as well as phosphorus and nitrogen pollution from manure and fertiliser damaging terrestrial and aquatic ecosystems (Diaz and Rosenberg, 2008). Increasing demands for food, particularly meat, combined with the need to sustainably feed a global population of 9.6 billion by 2050, while also lowering emissions and tackling environmental challenges, is driving innovation in protein sources for food and feed for both people and animals (Searchinger et al., 2013). Insects are a key alternative food source under investigation (Ordonez-Araque and Egas-Montenegro, 2021; Ruby and Rozin, 2019) being more sustainable due to their higher feed conversion efficiency, and lower greenhouse gas emissions and water and land use demands, compared to conventional meat and animal protein sources (Miller et al., 2016). Using insects to convert waste into animal feed is one option to improve sustainable consumption. However, Grinberga-Zalite and Zvirbule (2022) also note the need for food sector action to reduce food waste by implementing food donations and recycling non-food products.

Black soldier fly larvae (BSFL) have an outstanding ability to convert organic waste (consisting of mixed or separate waste) into biomass rich in fat and protein (Gao et al., 2019) and have good nutritional potential (Zozo et al., 2022; Bessa et al., 2020). BSFL can ingest a range of organic wastes including animal manure (Zhou et al., 2013), municipal organic waste (Kalova and Borkovcova, 2013), food waste (Salomone et al., 2017), crop straw (Manurung et al., 2016) and empty fruit bunches (Dickinson et al., 2019). Crude protein and crude lipid contents of BSFL

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meal range between 40%-44% and 15%–49%, respectively, depending on the processing methods and substrates used (Makkar et al., 2014). BSFL cannot transmit parasites or diseases when used in feed, despite feeding on waste, spoiled feed, and manure (van Huis et al., 2020).

Research in the wider project this paper stems from focuses on Malaysia, where over 80 million tonnes of oil palm biomass waste is generated annually (MIDA, 2021). Oil palm biomass can be converted to commercial products such as absorbent, fertiliser and animal food if the required nutritional values can be achieved (Umana et al., 2020), but many other feedstocks offer potential as well.

Food waste treated with insects is widely recognised as an environmentally friendly approach for recycling wastes with an additional benefit of low installation costs (Kim et al., 2021). However, aspects such as acidity, humidity, adequate temperature and feed components for insects to thrive and survive need all to be considered (Yoon et al., 2020). In this case, BSFL is gaining special attention for food waste treatment (Lalander et al., 2019). Depending on the substrates used, the quantity and quality of the nutritional value of BSFL varies. The growth of BSFL is significantly affected by the composition of the feed (Fu et al., 2022). It is thus advisable to use a supply of consistently similar resource material as different waste streams affect the final quality of the larvae. Using waste as resource to produce high quality protein BSFL reduces dependence on expensive protein sources including fishmeal and soy, brings the system closer to zero waste and positively impacts on the environment (Mohan et al., 2022). Economic benefits may be harnessed from BSFL as well, with BSF meal offering promising market opportunities. BSF meat has a worth of 400 billion USD to meet world feed production demand of 1 billion tonnes, as reported by the International Industry Federation in 2017 (Joly and Nikiema, 2019). Similarly, the economic feasibility of BSF production is expected to have vast global market potential as the animal feed market grows (Lalander et al., 2015; Makkar et al., 2014).

There are however, many stakeholders with different perspectives in the BSFL value chain and who are affected by BSFL production. For example, studies by Chen et al. (2020) and Jamaludin et al. (2021) questioned the halal compliance of meat based on BSFL grown on faeces and used for consumption in Islamic communities. Other researchers propose that religious perspectives on allowing certain types of food for insect farming feed should be considered (Liu et al., 2022). The literature is nevertheless lacking insights into different stakeholder views. At the same time, there is no information on stakeholders' perspectives regarding what an enabling environment for BSFL based animal feed production should look like. An enabling environment includes the practices, policies and attitudes which encourage people to take action and help them to succeed (THP, 1994), as well as factors concerned with effective governance and institutions within a particular sector and an individual country. Developing an enabling environment is vital if BSFL production for use in animal feed is to achieve its potential in addressing environmental sustainability goals.

This study addresses this knowledge gap, aiming to identify opportunities, challenges and solutions in political, economic and resourcing, institutional and legal, social and cultural aspects for BSFL-based animal feed production in Malaysia. Malaysia is a developing country that is struggling to advance a low carbon economy, has a growing population and an urgent need to combat climate change (Rahman, 2018). The country contributes 0.52% of the world's carbon emissions and is the fourth highest greenhouse gas emitter in the region after Indonesia, Vietnam and Thailand (Rahman, 2018). Malaysia has committed to reduce emissions by 45% by 2030 through the Paris Agreement (UNFCCC, 2015). Providing an enabling environment for BSFL business development could help meet those commitments while also addressing other development needs in line with the country's commitment to the SDGs.

We draw on data from interviews with stakeholders in Malaysia, applying thematic analysis and the analytic hierarchy process (AHP; a prioritisation and ranking tool (Saaty, 1987)) to identify actions that could support an enabling environment for BSFL-based animal feed.

## 2. Methods

Literature review was first undertaken to examine existing knowledge of the potential for BSFL to support the achievement of individual SDGs. The process flow (Fig. 1) then started with the preparation of interview questions and design of the analytical framework. Interview questions sought to capture opportunities for BSFL-based animal feed production at organisational, national and global scales, while challenges and solutions sought to capture political, economic and resourcing, institutional and legal and social and cultural considerations (see Supplementary Material). Ethical approval was obtained prior to data collection. Data collection focused on stakeholders based in Malaysia.

Data were analysed using thematic analysis and the AHP, allowing us to develop policy and societally relevant recommendations.

### 2.1. Interviews

Stakeholder analysis identified possible individuals and stakeholder groups working in Malaysia, along with their interest in and influence on BSFL-based animal feed production (Reed et al., 2009). Our stakeholder analysis results were cross-checked by 23 key informants from research and BSFL sectors. Snowball sampling was used to recruit participants from high interest groups (Fig. 2). High interest groups are those directly affected by or who can directly affect the outcomes of BSFL based animal feed production. We began with individuals within each group for whom we had contact details, who we then asked to identify further similar and different potential interviewees. Some of the initial interviewees contacted those they recommended to see if they were interested in participating. This approach enhanced the acceptance rate compared with an approach where invitations to participate came from researchers unknown to the potential participant (Reed et al., 2009). One limitation of snowball sampling is that those suggested may be biased by the social network of the recommending party. This was addressed by using multiple starting points which avoided a linear recruitment process. Overall, our sample included most of the key stakeholders except for those from government ministries. We did not manage to interview politicians or other key players from ministries. Despite invitations and reminders, responses were not received. As the industry is not yet well established in Malaysia, the project team considered it too early to assess the opinions of the general public, particularly when they would not be familiar with the barriers and opportunities. As such, we did not include the general public as a stakeholder group.

A project information sheet and the interview objectives were emailed to interviewees in advance, prior to gaining their consent to participate. Participants received detailed explanations on anonymity and confidentiality protection procedures, covering both the interview process and subsequent data storage and analysis. Interviews were conducted from February 2021–April 2021 with 19 interviewees spanning 8 stakeholder groups and involving 8 women and 11 men (Table 1). We placed utmost importance in seeking gender equality among respondents, in line with SDG 5, despite men dominating some of the stakeholder groups. All the industries and organisations involved were based in Malaysia. Of the 19 interviews, 4 were in Malay while the remainder were in English. Engagement modes included online and telephone interviews. Of the 19 interviewees, 16 were interviewed through an online platform, Webex; 2 answered the interview questions directly through a Google form and the remaining 1 was interviewed by telephone. Interview duration ranged between 40 and 90 min. Most of the discussions were recorded through Webex, with 1 being audio-recorded. We stopped at 19 interviewees as we reached saturation point upon reaching the 18th and 19th interviewees, with similar information being shared to that which we already had.

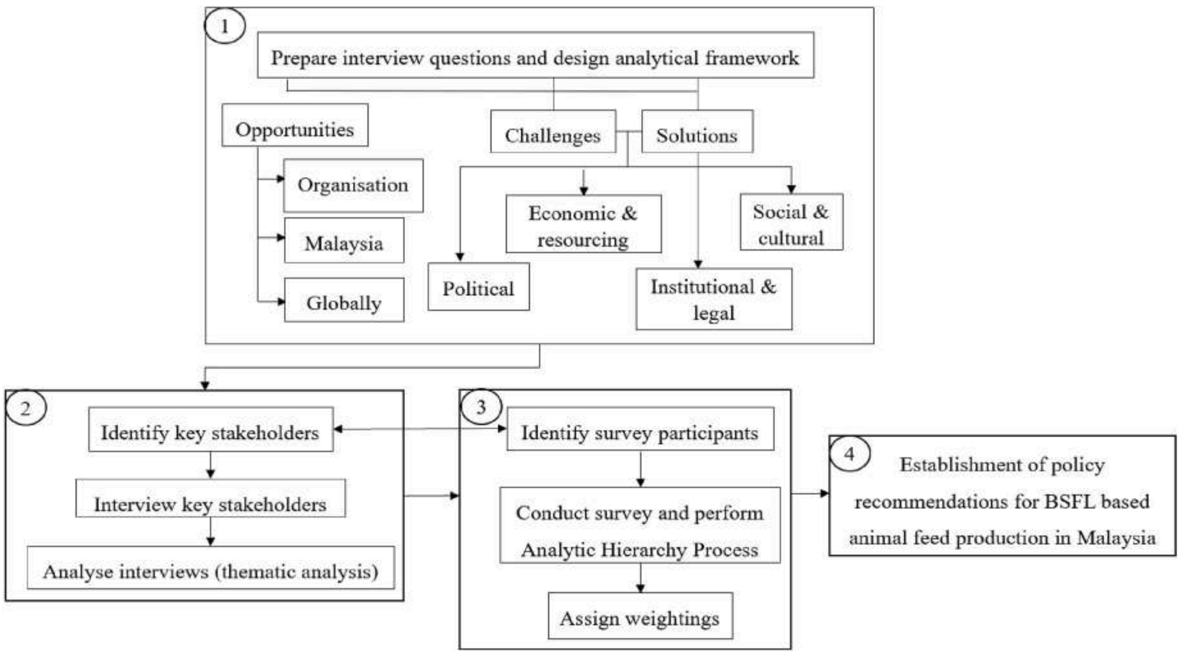


**Fig. 1.** Process flow of the research showing the order in which the different research steps were taken.

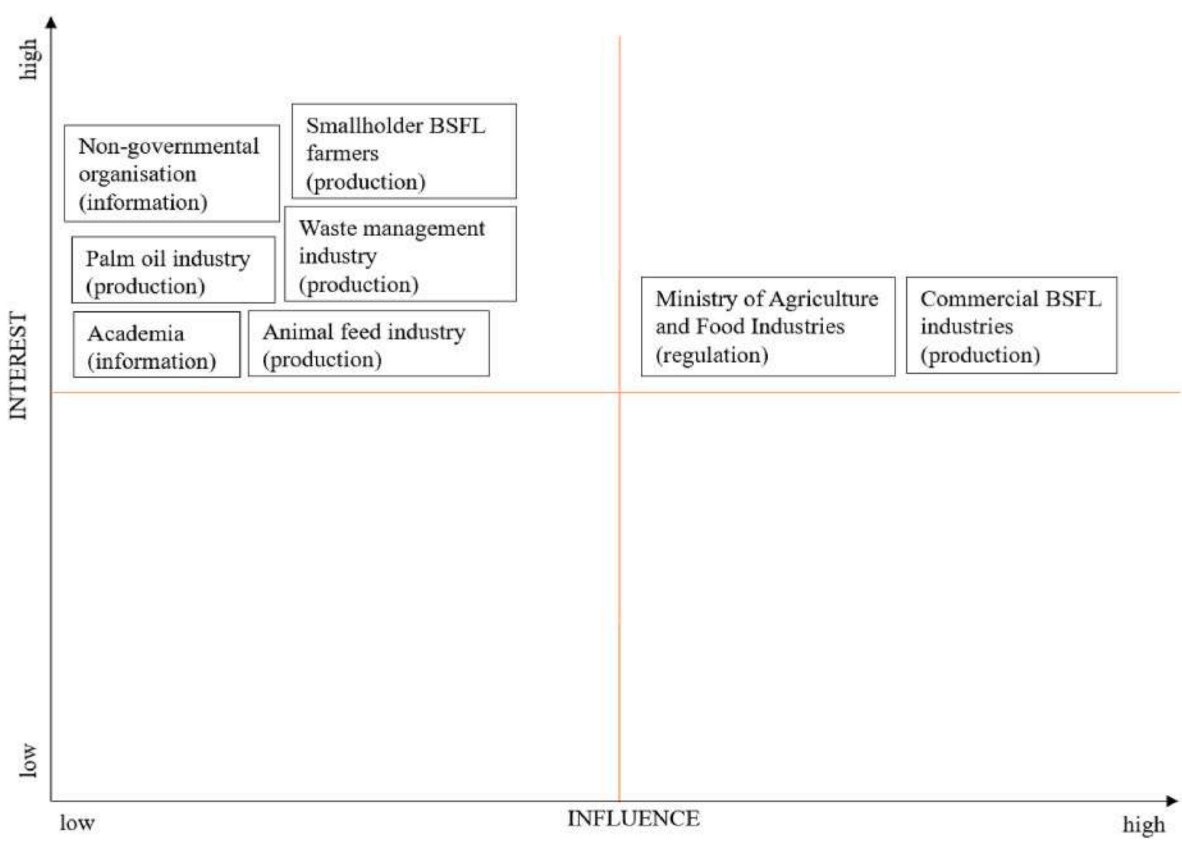


**Fig. 2.** Stakeholder interest-influence matrix showing the eight stakeholder groups deemed to have high levels of interest in BSFL production who were targeted for interview.

### 2.2. Thematic analysis

Interview recordings were transcribed in their original languages. For the analysis, selected relevant excerpts in Malay were translated into English once initial themes had been identified. Data were analysed using thematic analysis, which allowed us to identify, analyse and report similar patterns (themes) within transcribed data (Braun and Clarke, 2006; Vaismoradi et al., 2013). Opportunities were categorised at multiple scales (organisational, national and global) while responses regarding challenges and solutions were grouped under 4 themes:

**Table 1**
Distribution of interviewees.

| No. | Stakeholder group | Designation | No. of interviewees |
|---|---|---|---|
| 1 | Smallholder BSFL farmers | Farmers | 3 |
| 2 | Non-governmental organisation | Scientist | 1 |
| 3 | Waste management industry | Business executive | 1 |
| 4 | Animal feed industry | Feed formulator, international sales director | 2 |
| 5 | Palm oil industry | Agriculture officer | 1 |
| 6 | Academia | Senior lecturers, Associate Professors | 4 |
| 7 | Ministry of Agriculture and Food Industries | Research officers | 2 |
| 8 | Commercial BSFL industries | CEOs, R&D manager, Entomologist, Communication director | 5 |

'political', 'economic and resourcing', 'institutional and legal' and 'social and cultural'. Challenges and solutions for BSFL-based animal feed production in Malaysia shared by each interviewee were coded and grouped under the relevant themes. Challenges and solutions were further analysed by conducting a questionnaire survey which followed the analytic hierarchy process (AHP).

### 2.3. Analytic hierarchy process (AHP)

AHP is increasingly used to demonstrate and quantify experts' perspectives (Dalalah et al., 2010). Following analysis of the interview data, a survey was conducted with 9 experts (5 men and 4 women), from 8 stakeholder groups based on the interest-influence matrix developed at the start of the research, following the AHP process (Fig. 1). Participating experts were selected among our interviewees and had a minimum of 5 years' work experience in their respective field. Survey questions addressed all the challenges and solutions emerging from the interviews. Only 1 stakeholder group (BSFL industry, deemed to have the highest level of interest) had 2 experts participating, while the remaining stakeholder groups each had 1 participant, giving a total of 9 experts. This sample size is suitable given researchers are still unable to agree on a fixed number of respondents needed to justify the reliability of the results obtained from AHP research (Ghimire and Kim, 2018). The questionnaire survey was conducted online using Webex.

AHP follows four steps (Saaty, 1987): 1) define the problem and form a hierarchy with the aim at the top-level; 2) formulate pairwise comparison surveys or a questionnaire for experts to give their point of view based on a nine-point scale; 3) construct a pairwise comparison matrix with respect to the challenges and solutions listed under each of the main themes, based on the data obtained under step 2. When more than one respondent is involved in the AHP method, the geometric mean method (GMM) is used to obtain consensus in the pairwise judgement (Ishizaka and Nemery, 2013), (equation (1)). A set of eigenvectors that function as local priorities in a complete square matrix is developed using the GMM. The priorities show the relative importance of the elements within its range of category and on the element in the level above its range (Saaty, 1987). Fig. 3 shows the framework of GMM calculation, which is performed by multiplying each element in each row and taking their nth root (Saaty, 1987).

4) Measure the degree of randomness in the judgements used to develop the matrix (Sinha and Labi, 2007), taking into account the Consistency Ratio (CR). The CR measures the consistency in judgement (Saaty, 1987) and is calculated using the formula in equation (2). If the CR < 0.1, it can be assumed that the judgement matrix meets the consistency requirements (Chen and Dai, 2021). The Consistency Index (CI) is calculated through the difference of the largest eigenvalue ($\lambda_{max}$) to the number of attributes (n) in each category (equation (3)). The Random Index is the CI measured for each matrix of size n with random matrices (Saaty, 1987).

$$P_j = \sqrt[n]{\Pi_{i=1}^{n} a_{ij}} \tag{1}$$

where:

$P_j$: Pairwise judgement
n: number of elements
$\prod$: Product
$a_{ij}$: preference of alternative 'i' over alternative 'j'

$$CR = CI/RI \tag{2}$$

where:
CR: Consistency Ratio.
CI: Consistency Index.
RI: Random Index

$$CI = (\lambda_{max} - n)/(n-1) \tag{3}$$

where:

$\lambda_{max}$ : largest eigenvalue

n: number of attributes.

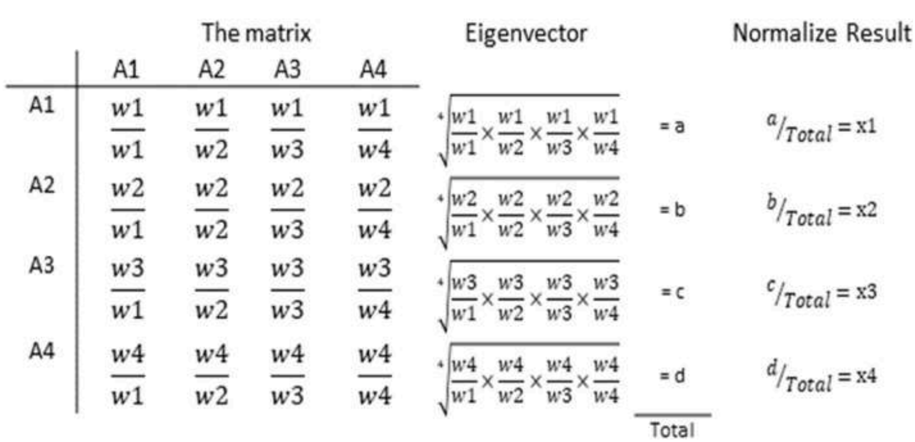


**Fig. 3.** Framework of geometric mean method (GMM) calculation used to calculate the priority weight for policy recommendations (Saaty, 1987). A represents the elements compared, w depicts the division of the nine-point scale assigned, a-d are the values of the root product, and x is the priority weight.

## 3. Results

### 3.1. Opportunities for BSFL based animal feed production

Opportunities for BSFL based animal feed production identified by interviewees considered: i) the ways in which production is organised, ii) opportunities at the Malaysian scale and iii) opportunities globally. Eight opportunities emerged at organisational level, four at Malaysia level and five at global level (Fig. 4 and Fig. 5), with some divergence in the opportunities recognised by different stakeholders.

BSFL produced at a large-scale can be marketed locally and commercial BSFL industries could expand and look to export BSFL products. Smallholder BSFL farmers could substitute costly animal or fish feed with low-cost BSFL as an alternative protein source for local poultry and aquaculture. Smallholders and animal feed industry interviewees reported this as an opportunity to reduce dependence on imported and high-cost animal feed while academics saw opportunities to use BSFL as an alternative feed for animals and fish.

Research has investigated the potential for BSFL to degrade empty fruit bunches from the oil palm industry which is substantial in Malaysia (Dickinson et al., 2019), with the best experimental conditions emerging as pH 6 with a 2:1 digestate:empty fruit bunch ratio using pre-processed empty fruit bunches using ionic liquid before anaerobic digestion. The interviewee from the palm oil industry reported using BSFL as an alternative feed source in aquaculture activities, considering it cheaper than fishmeal. However, the interviewee from the Ministry of Agriculture and Food Industries mentioned that the current price of BSFL is similar to that of fishmeal, so despite its potential, BSFL's competitiveness (both in terms of price and nutritional value) needs improvement before it could replace fishmeal.

Interviewees felt that BSFL produced in Malaysia could reduce dependence on imports and indirectly strengthen the local economy, opening the way for more BSFL business development nationally. Globally, BSFL business development yields an opportunity to initiate a zero-waste campus according to academics, helping to reduce food waste in cafeterias and colleges and other institutional settings (prisons, hospitals etc). Segregated food waste from the community and oil palm wastes could be used as feed for BSFL. An NGO interviewee mentioned that there is a good opportunity for production and insect milling in remote areas, supporting livelihood options in rural locations. Overall, opportunities were identified that target multiple SDGs (Fig. 6), supporting the potential already identified in the literature.

### 3.2. Challenges and solutions for BSFL based animal feed production

Detailed explanations of each challenge and solution identified for each of the main themes, illustrative interview quotes, and the priority weight calculated using AHP, are reported below. Further interview quotes and evidence are presented in the Supplementary Material (see SU-Table 1- SU-Table 4).

#### 3.2.1. Political aspects

With respect to the 'political' challenges, '*need to convince the government of the potential use of BSFL as an animal feed ingredient*' (77.5%) is viewed as more challenging than the problem of being '*unable to classify the land rented to build the BSFL industry*' (22.5%). Interviewees find it difficult to build confidence and political will of those with decision power that they should actively replace regular animal feed with insect meal, particularly as it is still a new and developing business in Malaysia. They felt that '*increased demand and interest in BSFL industries may change the perception of the government*' (71.9%) which was ranked highest in the AHP, followed by '*establish insect production*' (28.1%). Political will and support from the government was therefore felt to strongly influence BSFL business development in Malaysia. Political challenges and solutions are shown in Table 2. The CR is 0.000 for both the challenges and solutions.

#### 3.2.2. Economic and resourcing aspects

In terms of 'economic and resourcing' challenges (Table 3), '*high capital and operational costs to build and run the BSFL production system*' (21.8%) was ranked highest, while '*identifying a cost-effective BSFL production system*' (19.5%) ranked highest in terms of 'economic and resourcing' solutions. Most BSFL industries operating in Malaysia are self-funded which could explain the preference for this solution over that of relying on the assumption that '*industrial demand will attract government to provide* funding *for BSFL based production*' (9.3%). The second highest ranked 'economic and resourcing' challenge was '*challenges in ensuring a constant and sufficient supply of organic waste of BSFL*' (14.5%). This could be addressed by '*sourcing organic waste by partnering with a wide range of suppliers*' (12.9%).

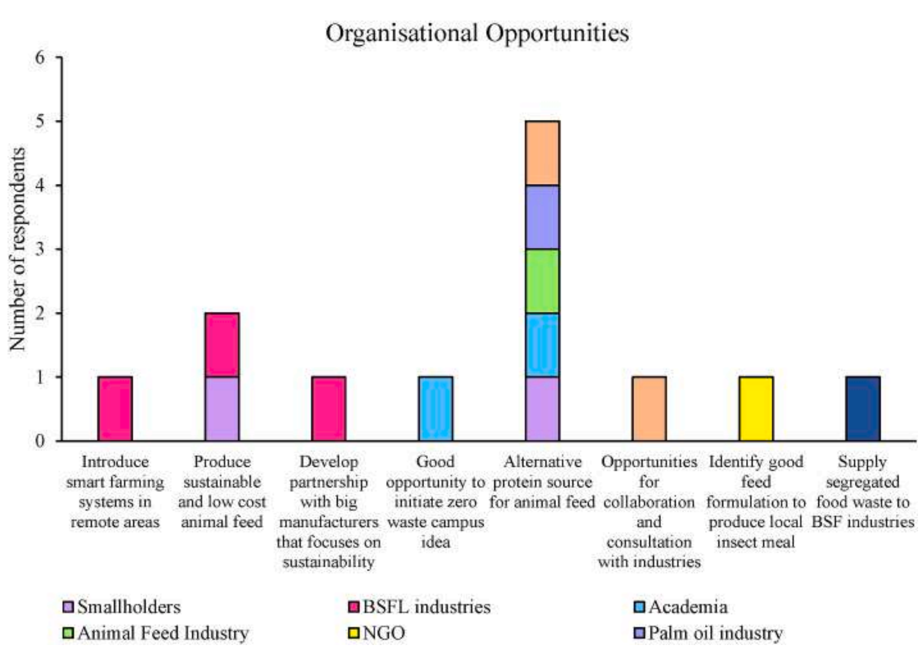


**Fig. 4.** Organisational opportunities for BSFL based animal feed production identified by each stakeholder group.

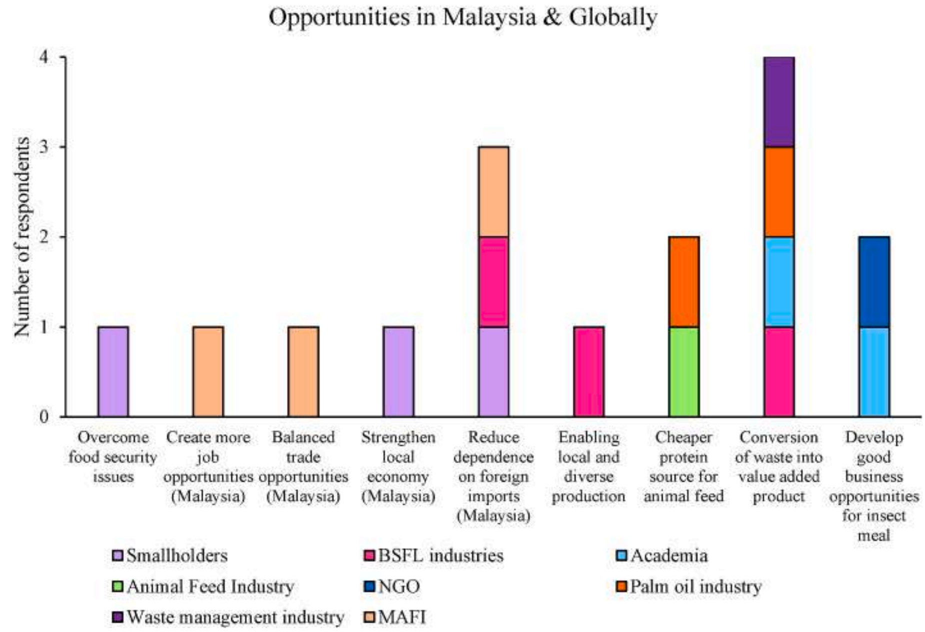


**Fig. 5.** Opportunities in Malaysia and globally for BSFL based animal feed production identified by each stakeholder group.

'*High price of BSFL*' (11.8%) was ranked third highest followed by '*challenges in obtaining constant BSFL supplies as an animal feed ingredient*' (10.3%) and '*lack of financial resources to conduct research*' (9.1%). These challenges were considered best addressed by experts by setting '*reasonable pricing for BSFL based products to be set by BSFL industries*' (16.7%), '*optimising the production of BSFL*' (9.2%) and '*providing grant funding opportunities*' (5.9%). 'Economic and resourcing' challenges on '*lack of knowledge on insect studies and skilled expertise to work in BSFL industries*' (9.1%) and '*lack of education of workers in food and beverage departments to segregate food waste in an industry with high staff turnover*' (8.7%) can be addressed by '*providing training for the younger generation by introducing industrial insect course in universities and for workers in the food and beverage industries*' (7.8%) as suggested by the interviewees. The eighth ranked challenge was '*high costs of a large supply of feed source for BSFL*' (9.0%) with the suggested solution to '*implement the good practice of food waste segregation among the community*' (11.7%). The lowest ranked was '*challenges in ensuring constant BSFL nutrient quality as an animal feed ingredient*' (5.6%). The solution for this challenge is to '*conduct more research on BSFL nutrient quality*' (7.2%). The CR is 0.008 for both the challenges and solutions.

### 3.2.3. Institutional and legal aspects

'*Lack of coordination for documentation processing between regulatory authority in headquarters and within the states*' (49.7%) was found to be the highest priority within the 'institutional and legal' challenges (Table 4). Better coordination and communication mean processes become easier, quicker and more efficient. Respondents felt the best way to address this is to '*standardise the regulations and processes between the regulatory authority in headquarters and within the states*' (48.4%). The second and third most prioritised challenges were '*no guidelines to control bad odour from BSFL rearing areas*' (30.9%) followed by '*no halal certifications for BSFL feed*' (19.4%). Respondents considered they could be addressed by '*conducting regular inspections to prevent the spread of bad odour from the BSFL rearing area*' (29.0%) and '*introducing halal certification to standardise the list of substrates to be used as feed for BSFL*' (22.6%). The CR is 0.002 for both the challenges and solutions.

### 3.2.4. Social and cultural aspects

'*Public concerns about smell and hygiene for BSFL rearing area*' (61.2%) was the highest priority 'social and cultural' challenge (Table 5). One interviewee shared that they had to close a BSFL business because the community nearby complained regarding bad odour coming from their BSFL rearing area. The solution to the odour issue suggested by interviewees was to '*spray effective microbes to overcome odour issues from the BSFL rearing area*' (8.2%). This worked for one of the interviewees but others disagreed and emphasised proper ventilation. The second most highly prioritised challenge was '*public perception of BSF as yucky insect*' (21.6%) and '*public perception of BSF as a pest for stingless bees*' (17.1%). There are a few solutions for these challenges: '*organise awareness programs for the public*' (30.5%), '*organise insect industrial visits to demonstrate the potential and safety of using BSFL*' (27.5%), '*educate at school and universities about the potential use of BSFL*' (26.1%) and with the lowest rank '*distribute samples of BSFL products in public areas*' (7.6%). The CR for the challenges and solutions is 0.001 and 0.003, respectively.

## 4. Discussion

Opportunities for BSFL use in animal feed to contribute towards each of the SDGs were identified in the literature (Fig. 6), whereas the interviewees identified opportunities linked to eight SDGs (Fig. 6; SDGs 1, 2, 3, 8, 9, 12, 13 and 17). However, there are several challenges in using BSFL-based animal feed production. Addressing these challenges requires multiple solutions targeting each of the political, economic and resourcing, legal and institutional, and social and cultural aspects that were considered.

The most common political challenge faced by most of the interviewees was to '*convince the government of the potential use of BSFL as an animal feed ingredient*'. BSFL enterprises are still new but a fast-growing industry. One of the interviewees faced challenges in convincing the government to secure a BSFL based project back in 2018 because the authorities insufficiently appreciate the potential of using BSFL to convert waste into value added products. However, '*increased demand and interest in BSFL industries*' could eventually change the perception of the government towards BSFL industry, as suggested by the interviewees. When there is an increased demand for BSFL, it is likely there will be a rise in number of new companies joining the production market and investing in research and development, creating more competition (Wang and Shelomi, 2017) which would eventually demonstrate the potential and enthusiasm about BSFL. Global drivers such as countries' commitments to reaching net zero carbon emissions

| Goals | Potential impacts | Opportunities identified by stakeholders |
|---|---|---|
| 1 NO POVERTY | • New economic opportunities arising from BSFL production can improve the social status and livelihood of smallholder farmers (Chia et al., 2019) helping to bring them out of poverty (Barragan-Fonseca et al., 2020), while at a national level, BSFL offer potential to increase gross domestic product (GDP) (Moruzzo et al., 2021).<br>• Locally produced BSFL with easy rearing techniques may reduce dependence on foreign feed imports particularly for smallholder farmers, opening routes for smallholders to participate in the global market (Barragan-Fonseca et al., 2020). | • Create more job opportunities<br>• Reduce dependence on foreign imports |
| 2 ZERO HUNGER | • BSFL have the potential to become a sustainable and healthy food and feed alternative to conventional animal feed sources (Shumo et al., 2019) that can be a part of the human food chain.<br>• Insect rearing helps to promote sustainable agriculture that can help support zero hunger into the future (Barragan-Fonseca et al., 2020). | • Produce sustainable and low-cost animal feed<br>• Alternative protein source for animal feed<br>• Cheaper protein source for animal feed |
| 3 GOOD HEALTH AND WELL-BEING | • Good quality food helps to improve health and well-being of all age groups through improved nutrition (Moruzzo et al., 2021). BSFL produced | • Alternative protein source for animal feed<br>• Identify good feed formulation to produce local insect meal |

**Fig. 6.** Potential impacts of edible insects and BSFL in progressing towards the SDGs as identified both in the literature and by stakeholders in this research (Abro et al., 2020; Banks et al., 2014; Barragan-Fonseca et al., 2017, 2020, BEF, 2021, TRF, 2020; Bullock et al., 2013; Celitron, 2019; Dicke, 2018; Diener et al., 2009; Dobermann et al., 2017; Ekins et al., 2019; Hanboonsong et al., 2013; Lane, 2018; Madau et al., 2020; Mahmood et al., 2021; McLaren et al., 2020; Mohamad et al., 2020; Moruzzo et al., 2021; Nugroho et al., 2019; Oonincx and de Boer, 2012; Parodi et al., 2020; Perednia et al., 2017; Sarpong et al., 2019; Setti et al., 2019; Shumo et al., 2019; Siddiqui et al., 2022; SNRD Africa, 2021; Stockholm, 2015; Velenturf et al., 2019; Wang et al., 2017).

| | | |
|---|---|---|
| | locally can improve access to protein (Mohamad et al., 2020) when the animals fed with insects are consumed by humans. | |
| 4 QUALITY EDUCATION | • Income from BSFL production could increase household income of smallholder farmers (TRF, 2020) which could increase the proportion of children in education (Lane, 2018). | - |
| 5 GENDER EQUALITY | • Women's participation is unlikely to substantially affect their community responsibilities and family duties (McLaren et al., 2020) as small-scale BSFL production can be carried out at home.<br>• BSFL production can create job opportunities for women (TRF, 2020), giving them a greater say in income expenditure decision making and empowering them (SNRD Africa, 2021) through development of new skills. | - |
| 6 CLEAN WATER AND SANITATION | • BSFL breeding practically needs only minimal space (Kim et al., 2021) and very little water.<br>• BSFL can feed on human waste and help to alleviate sanitation issues (Dicke, 2018; Banks et al., 2014). | - |
| 7 AFFORDABLE AND CLEAN ENERGY | • Insect farming can convert crop residues into simple organic materials supporting biofuel production (Wang et al., 2017), as well as reducing air pollution (Moruzzo et al., 2021). | - |

**Fig. 6.** (*continued*).

| | | |
|---|---|---|
| 8 DECENT WORK AND ECONOMIC GROWTH | • Development of BSFL production can open opportunities for entrepreneurship and innovation, supporting the growth of small and medium sized enterprises (Ravi et al., 2020; Sarpong et al., 2019) and youth employment (TRF, 2020; Abro et al., 2020).<br>• Economic opportunities in terms of contribution to the global edible insect market are expected to touch USD 7.96 billion by 2030 with the aid of compound annual growth rate of 24.4% over the forecast period of 2019-2030 (Nugroho et al., 2019). Opportunities for import and export of insects for food throughout South-East Asia in which Thailand's import market alone reached 1.14 million USD/year (Hanboonsong et al., 2013). | • Create more job opportunities<br>• Balanced trade opportunities<br>• Strengthen local economy |
| 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE | • The practice of starting up insect farming with small capital and operational costs and basic knowledge on insect farming can be introduced in low-income countries with minimum levels of guidance and instruction (Moruzzo et al., 2021) supporting more inclusive and sustainable industrialisation.<br>• Industrial scale insect production helps to sustain long-term insect availability (Moruzzo et al., 2021), making incorporation into fish and livestock feed more feasible as a supply chain and industrial development opportunity. | • Introduce smart farming systems in remote areas<br>• Create more job opportunities<br>• Develop good business opportunities for insect meal |

**Fig. 6.** (*continued*).

| | | |
|---|---|---|
| 10 REDUCED INEQUALITIES | • Development of insect industries can help to reduce economic gaps as a novel income stream across scales (Moruzzo et al., 2021).<br>• Low start-up costs offer potential for NGOs to support development of the poorest and most marginalized groups e.g., those in conflict zones or refugee camps, through provision of BSFL inputs and training (BEF, 2021), helping to reduce inequalities.<br>• BSFL farming offers opportunities for rural communities to be part of the economic value chain, resulting in a good profit and improving their livelihood (Diener et al., 2009), which reduces inequalities within countries (Barragan-Fonseca et al., 2020). | - |
| 11 SUSTAINABLE CITIES AND COMMUNITIES | • BSFL can be produced in rural communities (Bullock et al., 2013) offering local income streams and value chains for BSFL development (Stockholm, 2015).<br>• BSFL can be grown sustainably within cities, using less space than other animals (Celitron, 2019; Oonincx and de Boer, 2012) and presenting opportunities for waste reduction as food and other waste can be used as feedstock (Kim et al., 2021). | - |
| 12 RESPONSIBLE CONSUMPTION AND PRODUCTION | • Using BSFL for animal feed production and bio-conversion of waste (e.g., castings or frass) into value added products such as fertiliser offers opportunities | • Supply segregated food waste to BSFL industries<br>• Conversion of waste into value added product |

**Fig. 6.** (*continued*).

| | | |
|---|---|---|
| | for a circular economy model (Barragan-Fonseca et al., 2017; Setti et al., 2019). Circular economy approaches aim to build natural, social and economic capital by keeping the products and waste materials in use, therefore aiding regeneration of natural systems (Velenturf et al., 2019; Ekins et al., 2019). | • Enabling local and diverse production |
| 13 CLIMATE ACTION | • Direct methane and nitrous oxide emissions during BSFL rearing are 16.8 ± 8.6 g of carbon dioxide ($CO_2$) equivalent per kg of dry BSFL biomass with very low ammonia emissions (negligible and can be avoided before the $CO_2$ value peaks) (Parodi et al., 2020). BSFL has the potential to recycle carbon into oils and edible protein instead of breaking down to methane and $CO_2$, reducing greenhouse gas emissions (Perednia et al., 2017). | • Conversion of waste into value added product<br>• Good opportunity to initiate zero waste campus idea |
| 14 LIFE BELOW WATER | • BSFL farming can support sustainable utilisation of marine resources (Moruzzo et al., 2021) when the insects are able to partially or fully substitute fish oil and fishmeal in animal and fish feed, supporting efforts to reduce overfishing and illegal or unregulated fishing (Moruzzo et al., 2021). | - |
| 15 LIFE ON LAND | • BSFL farming could support efforts to reduce biodiversity loss as a result of lower demands for land and thus less land use (Madau et al., 2020) conversion | - |

**Fig. 6.** (*continued*).

| | | |
|---|---|---|
| | and deforestation (Moruzzo et al., 2021).<br>• Residue from insect farming (e.g., 20% of residue from BSFL treatment) can be used as a soil amendment / compost, improving soil quality and reducing waste disposal demands (Mahmood et al., 2021; Siddiqui et al., 2022). | |
| 16 PEACE, JUSTICE AND STRONG INSTITUTIONS | • Many different stakeholders (government, industries and institutions) are engaged in the BSFL industrial pipeline. Supporting insect-based industries can enable opportunities for dialogue, increased understanding and set the foundations for peace (Barragan-Fonseca et al., 2020).<br>• Proper regulation that takes into account multiple stakeholder perspectives is crucial to support the BSFL production supply chain and could drive up food quality standards and enforcement (Dobermann et al., 2017). | - |
| 17 PARTNERSHIPS FOR THE GOALS | • BSFL production offers opportunities for new collaborations (e.g., between governments, donors industries, producers, exporters, retailers, and consumers) with partnerships supporting progress towards multiple SDGs, including through investment in strengthening science, technology and innovation capacity (Walter et al., 2020). | • Develop partnership with big manufacturers that focuses on sustainability<br>• Opportunities for collaboration and consultation with industries |

**Fig. 6.** (*continued*).

could potentially leverage investment in this area as well. However, there are constraints to BSFL use in the poultry industry at a large scale. The price of BSFL may not be competitive compared to conventional protein sources and involves drastic changes to the current BSFL production system to produce BSFL at scale with an attractive price. Nevertheless, in some countries, BSFL is still an attractive feed

**Table 2**
Political challenges and solutions for BSFL based animal feed production and their priority weightings.

| Themes | Sub-themes | Priority weight (%) | Themes | Sub-themes | Priority weight (%) |
|---|---|---|---|---|---|
| Political (challenges) | Need to convince the government of the potential use of BSFL as an animal feed ingredient | 77.5 | Political (solutions) | Increased demand and interest in BSFL industries may change the perception of the government | 71.9 |
| | Unable to classify the land rented to build the BSFL industry | 22.5 | | Establish insect production | 28.1 |

**Table 3**
Economic and resourcing challenges and solutions for BSFL based animal feed production and their priority weightings.

| Themes | Sub-themes | Priority weight (%) | Themes | Sub-themes | Priority weight (%) |
|---|---|---|---|---|---|
| Economic and resourcing (challenges) | High capital and operational costs to build and run the BSFL production system | 21.8 | Economic and resourcing (solutions) | Identify a cost-effective BSFL production system | 19.5 |
| | | | | Industrial demand will attract the government's attention to provide funding for BSFL based production | 9.3 |
| | Challenges in ensuring a constant and sufficient supply of organic waste for BSFL | 14.5 | | Source organic waste by partnering with a wide range of suppliers | 12.9 |
| | High price of BSFL | 11.8 | | Reasonable pricing for BSFL based products to be set by BSFL industries | 16.7 |
| | Challenges in obtaining constant BSFL supplies as an animal feed ingredient | 10.3 | | Optimise the production of BSFL | 9.2 |
| | Lack of financial resources to conduct research | 9.1 | | Provide grant funding opportunities | 5.9 |
| | Lack of knowledge on insect studies and skilled expertise to work in BSFL industries | 9.1 | | Provide training for the younger generation by introducing industrial insect course in universities and for workers in the food and beverage industries | 7.8 |
| | Lack of education of workers in food and beverage departments to segregate food waste, in an industry with high staff turnover | 8.7 | | | |
| | High costs of a large supply of feed source for BSFL | 9.0 | | Implement the good practice of food waste segregation among community | 11.7 |
| | Challenges in ensuring constant BSFL nutrient quality as an animal feed ingredient | 5.6 | | Conduct more research on BSFL nutrient quality | 7.2 |

**Table 4**
Institutional and legal challenges and solutions for BSFL based animal feed production and their priority weightings.

| Themes | Sub-themes | Priority weight (%) | Themes | Sub-themes | Priority weight (%) |
|---|---|---|---|---|---|
| Institutional and legal (challenges) | Lack of coordination for documentation processing between regulatory authority in headquarters and within the states | 49.7 | Institutional and legal (solutions) | Standardise the regulations and processes between the regulatory authority in headquarters and within the states | 48.4 |
| | No guidelines to control bad odour from BSFL rearing areas | 30.9 | | Conduct regular inspections to prevent the spread of bad odour from the BSFL rearing area | 29.0 |
| | No halal certifications for BSFL feed | 19.4 | | Introduce halal certification to standardise the list of substrates to be used as feed for BSFL | 22.6 |

**Table 5**
Social and cultural challenges and solutions for BSFL based animal feed production and their priority weightings.

| Themes | Sub-themes | Priority weight (%) | Themes | Sub-themes | Priority weight (%) |
|---|---|---|---|---|---|
| Social and cultural (challenges) | Public concerns about smell and hygiene for BSFL rearing area | 61.2 | Social and cultural (solutions) | Spray effective microbes to overcome odour issues from BSFL rearing area | 8.2 |
| | Public perception of BSF as a yucky insect | 21.6 | | Organise awareness program for the public | 30.5 |
| | | | | Organise insect industrial visit to demonstrate the potential and safety of using BSFL | 27.5 |
| | Public perception of BSF as a pest for stingless bee | 17.1 | | Educate at school and universities about the potential use of BSFL | 26.1 |
| | | | | Distribute samples of BSFL products in public areas | 7.6 |

ingredient for the poultry industry due to weak currency for importation of protein meal (Vilela et al., 2021). BSFL not only acts as good fatty acid and amino acid substitute in the poultry industry but also in aquaculture and petfood industry (Ravi et al., 2020). Freel et al. (2021) reported that BSFL oil and BSFL meal are suitable for consumption by dogs without affecting their safety and health. Multiple efforts are seeking a sustainable and suitable protein substitution for fishmeal in aquaculture industry, particularly with something that does not create rivalry with human food production and agricultural land (Colombo, 2020; Fisher et al., 2020). BSFL offers potential here as a promising alternative to fishmeal (English et al., 2021). For example, in trout grow-out diets, BSFL has the potential to replace 50% of fishmeal (Stamer et al., 2014) while for yellow catfish grow-out diets, BSFL can substitute 48% of fishmeal, engendering no changes in feed and growth conversion ratio, and simultaneously improving the capability of the fish's digestibility system (Xiao et al., 2018).

The majority of interviewees agreed that '*high capital and operational costs to build and run the BSFL production system*' is a major constraint for BSFL business development in Malaysia. It is envisaged that similar challenges would be met in other developing countries. One interviewee noted how capital-intensive BSFL production is, and that it requires a lot of investment, across both farming and processing. BSFL processing investments are largely due to the need for automation and technology to ensure the final BSFL product has constant nutritional value, as well as to train personnel to follow the required standards. In studies using BSFL as animal feed, modern technologies result in higher costs than the conventional technologies (Ignjatijević, 2010; Pleissner and Smetana, 2020). Labour costs account for 65% of the entire production cost when life cycle costs for small-scale production have been estimated (Joly and Nikiema, 2019), while other studies show labour acquisition and substrate result in approximately 90% of BSFL costs (Roffeis et al., 2018). The most prioritised solution by interviewees is to identify a '*cost-effective BSFL production system*'. This was also identified by researchers working in Brazil using insects as feed for poultry, highlighting the need to establish optimised and cost-efficient mass insect rearing facilities (Allegretti et al., 2018). Indeed, a useful way to evaluate the viability of a project is by conducting profitability analysis, in which the most common approach used is cost benefit analysis. Cost benefit analysis covers evaluation of payback period, internal rate of return, benefit cost ratio and net present value. Net present value, however, is the best indicator for evaluation compared to other three indicators (Oppong, 2017). There is a saying that goes "invest if the net present value of investing exceeds zero" which best reflects the profitability of a project (Basher and Raboy, 2018, p. 218).

In the study by Allegretti et al. (2018), findings showed that the renewability value increased by 45.64% while the transformity value decreased 144.74%. In insect meal production, the emergy yield ratio (EYR) reduced from 1.71 to 1.00 compared to soybean meal while the emergy sustainable index (ESI) increased from 0.86 to 0.96. (Renewability represents the ratio between renewable resources and total energy while tranformity refers to the ratio between total emergy and output energy. Emergy is consolidated energy needed to start-up a flow (Odum, 1996). EYR refers to the ratio between total emergy and non-renewable inputs whereas ESI is a ratio between yield ratio and environmental loading ratio). When insect meal was used instead of soybean meal, gains were observed in poultry production such as a 16.45% decrease in transformity of poultry meat, 25.03% increase in renewability, reduction in environmental loading ratio from 4.96 to 3.68 and increase in EYR from 1.33 to 1.41. These findings show BSFL meal has the potential to improve sustainability in Brazilian poultry production.

The nutrient quality of the BSFL produced varies according to the purpose of the BSFL product and thus the needs of the end consumer (depending whether it is used in poultry feed, aquafeed, or pet food). Standardising the substrate used to feed the BSFL can retain the nutritional quality of the BSFL produced. However, substrate from various waste streams affects the final quality of the BSFL. The protein nutritional pattern is affected by factors such as fatty acids, lipid and chitin content within their bodies, even though similar substrates are used. This acts as a barrier for BSFL production as a primary protein source for animal feed (Mohan et al., 2022).

Different rearing conditions also affect the growth and quality of the BSFL produced. For example, methionine, an important type of amino acid content in BSFL, can be increased by using almond hull as a growth substrate along with varying substrate carbon to nitrogen ratio, which is crucial for poultry industry. The density of methionine in BSFL increases by 25% upon increasing carbon to nitrogen ratio from 26 to 40 (Miner et al., 2022), while increasing moisture content and aeration rate help to increase the larvae weight without affecting cysteine and methionine of larvae content. Harvested larvae weight tripled with the increment in aeration rate from 0.04 to 0.36 mL/min while larvae weight increased by 56% with the increase in moisture content from 480 g/kg to 680 g/kg. In contrast, low aeration rate and moisture content create suitable environmental conditions for microbial activity in the substrate used (almond hull) over larvae growth and consumption (Palma et al., 2018). Furthermore, using different almond by-products (shells and hulls) affects the growth of larvae. Using pollinator hulls and Monterey as substrate resulted in higher average larvae weight of 109% and 158%, respectively, in comparison with mixed shells and nonpareil hulls. On the contrary, BSFL reared on mixed shells and Monterey showed highest values for cysteine and methionine contents compared to the remaining two substrates (Palma et al., 2020).

To maintain product quality and ensure consistent performance across feedstocks, large-scale BSFL treatment facilities must know how to pre-treat or blend the feedstock (Gold et al., 2020; Raksasat et al., 2020). Different techniques of preserving BSFL through freeze-drying and hot-air drying can prevent degradation and spoilage during storage. A study by Saucier et al. (2021) reported low water activity of below 0.4 for BSFL powder (derived from ground defrosted larvae) which was treated for 240 s in boiling water (able to reduce microbial load) prior to the drying process using hot air at 60 °C for 6 h. As a result, minimal colour changes were observed over a 30-day storage period, retaining the stability of the product (Saucier et al., 2021). For insect meal to be a major component of animal diets, it has to be processed and produced in large-scale and available year-round (Makkar et al., 2014). This relates to the '*challenges in obtaining constant BSFL supplies as an animal feed ingredient*'. Low nutrient quality of the BSFL produced can be partially overcome with large-scale nutritionally-balanced feed substrates for BSFL (Raksasat et al., 2020), but demands better BSFL feeding and feed formulation methods. While commercial BSFL industries tended to see quality as more important, smallholder BSFL farmer interviewees were less concerned. This suggests further information is needed for stakeholders to learn about each other's concerns and challenges.

From the BSFL industry perspective, they do not currently have issues with quality, but rather, ensuring the necessary quantity is produced at a reasonable cost. Smallholder BSFL farmers reported difficulties in bearing the '*high costs a large supply of feed source for BSFL*'. Costs of BSFL feed can amount to 70% largely due to the costs of protein components in the feed (Chia et al., 2019). It is crucial to have a large substrate supply for BSFL not only to accommodate large-scale production but also to help address low nutrient quality issues (Raksasat et al., 2020), particularly if involving smallholder producers.

Various kind of wastes have been used to grow BSFL in Malaysia including rice (Ong et al., 2017), vegetable and fruit waste (Ahmad et al., 2021), soybean curd and coconut endosperm (Lim et al., 2019), with considerable variation in development and growth across the substrates used (Sprangers et al., 2017; Lalander et al., 2019; Leong et al., 2016; Liu et al., 2020). BSFL has high fat content and is adaptive to various types of rice waste (Ong et al., 2017), while Ahmad et al. (2021) reported that fruit waste is potentially more suitable than vegetable waste for BSFL growth. Lim et al. (2019) monitored the development of protein nutritional content of BSFL using mixed soybean curd residue (SC-r) and waste coconut endosperm (w-CE). Bioconversion of a total of 68% of mixed SC-r and w-CE was successful. Interviewees suggested that besides varying waste suppliers, '*implementing good practise of food waste segregation among the community*' could also help to avoid the dependency on organic waste to feed BSFL that comes with a high cost.

In terms of 'institutional and legal' aspects, there is a need for proper regulation of the use of BSFL as animal feed in Malaysia, as has already been the case elsewhere, including in developing countries such as Uganda. According to one of the interviewees, there is a '*lack of coordination for documentation processing between the regulatory authority in headquarters and within the states*'. Better coordination could ease the process of applying for certification and documentation, attracting more investors to BSFL industries.

Poor public perception of BSFL in animal feed is one of the main social and cultural challenges. Mostly '*BSF is classified as a yucky insect*' and causes a bad odour. However, Higa et al. (2021) show that Americans were willing to eat the insects indirectly by eating animals fed with those insects instead of direct insect consumption and that BSFL are a promising alternative to the farmed animals most commonly used as pet food and are well accepted by consumers. UK consumers are willingly ready to trust and accept eggs from hens being fed with insects if introduced and produced with the animal welfare labels showing that the product is organic and free range. A considerable proportion of consumers were willing to pay 18% more for the eggs from hens fed with insects, proving the eggs have the potential to become a premium product in the UK market (Spartano and Grasso, 2021). Both these studies show that people are still willing to slowly change their mindset and accept BSFL as an indirect part of their diet. Naranjo-Guevara et al. (2020) further confirmed this but also that there is a need to educate and inform consumers about the health and environmental benefits of entomophagy so consumers can learn about the advantages of, and increase their level of familiarity with, insects as food. In the case of Malaysia, this would also be necessary as research on public opinions about insect consumption, both direct and indirect, is lacking. '*Organising awareness programs*' could also help change the unfavourable public perceptions of BSFL. Khaemba et al. (2021) reported that over 70% of respondents showed willingness and preference to eat eggs from hens fed with BSFL. Khaemba et al. (2021) concluded that providing evidence for BSFL-based feed in poultry and creation of increased awareness would foster uptake of this emerging and rapidly growing technology and improve consumer perception.

That '*BSF has been considered a pest for stingless bees*' is one of the 'social and cultural' challenges identified in our study. However, BSFL cannot transmit parasites or diseases and can be considered a non-harmful pest (compared with housefly or face fly larvae which go on to become pests (Raksasat et al., 2022)). Adult BSF do not cause any nuisance, nor are they attracted to human habitats. BSFL can even hinder the growth of microbial pathogens found in feeding substrates, and are able to survive in various range of environments (Cĭcková et al., 2015; Mohd-Noor et al., 2017). These characteristics makes BSFL suitable for animal feed (Chia et al., 2019). However, in 2016, a study reported that BSF had invaded stingless beehives in northern Peninsular Malaysia. Based on one of the studies on infestation of BSF on Indo-Malayan stingless bee colonies, decayed stingless bee hives and the sour smell of honey (honey spilled and flowed out of the nest) could be what attracted female BSF to lay their eggs on the nest or logs (Hashim et al., 2017; Ivorra et al., 2020). It is evident that BSF can invade beehives when the hives are poorly maintained, but this does not harm the stingless bees. Invasions can be avoided if beekeepers follow proper standard operating procedures and maintain their hives well.

'*Educating the younger generation at school and university level*' could further improve understanding and perceptions about the BSFL and its potential and safety, while educating and informing consumers about the benefits of feeding animals with insects could increase consumers' acceptance rate and overcome their fears over BSFL (Spartano and Grasso, 2021). Walter et al. (2020) promoted hands-on activities and research experiences through workshops using BSFL in schools and this successfully raised awareness about the potential of BSF. Hands-on work with insects increased excitement for the topic, decreasing negative connections with insects including scepticism and phobia (Walter et al., 2020). More emphasis should also be given to the benefits of feeding animals with insect meal to increase acceptance and awareness (Szendrő et al., 2020). Khaemba et al. (2021) reported that informing consumers through advertisements and alternative marketing policies may result in positive perception of food products. Again, public acceptance and support from relevant authorities are important in moving forward and expanding BSFL businesses as well as to increase the utilisation of eco-friendly BSFL in the food industry (Kim et al., 2021).

Overall, we have identified opportunities, challenges and solutions for BSFL-based animal feed production and shown how, with the necessary enabling environment, they offer potential to advance toward multiple SDGs. Our findings, empirically grounded in Malaysia, provide useful information reflecting the current situation for policymakers to make more effective decisions as policy to support BSFL-based animal feed production evolves.

Our largest potential limitations relate to the type and number of stakeholders involved in the interviews. Stakeholders from the ministries, including policymakers, were missing and the public were not targeted, yet they may help to inform further actions that could improve the enabling environment. We invited participation from ministries, followed up, and attempted to recruit respondents as they are a high interest and high influence group, but overall, responses were lacking. We deliberately did not involve the general public as one of our stakeholders at this point given low awareness about BSFL and the nascent stage of the industry in Malaysia.

For the AHP, a small sample size is not considered problematic. AHP may be applied from one to a large number of respondents (Ghimire and Kim, 2018), and all the calculated consistency ratio values were <0.1, thus, despite the small sample size, the results obtained are valid and reliable. Future researchers may wish to increase the number of respondents engaged in research on this topic, including other stakeholders. However, a greater number of respondents may result in data conflicts that prove difficult to resolve given the subjective nature of qualitative research.

Our findings and overall approach have wider applicability across other developing nations, as other countries seek to grow their insect-based animal feed production. The output of this research from Malaysia offers a benchmark case study for future researchers within Malaysia and globally, and provides important policy proposals for the Malaysian case. Actions are needed at multiple entry points across each of the categories we identified to develop an enabling environment to harness the benefits from BSFL production, minimise the barriers and risks, and to further strengthen the global industrial pipeline. Achieving this requires engagement of multiple stakeholders across public and private sectors, as well as on both supply and demand sides.

## CRediT authorship contribution statement

**Sharvini Siva Raman:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing. **Lindsay C. Stringer:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Neil C. Bruce:** Supervision, Project administration. **Chun Shiong Chong:** Supervision, Project administration.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The authors do not have permission to share data.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.133802.

## References


Abro, Z., Kassie, M., Tanga, C., Beesigamukama, D., Diiro, G., 2020. Socio-economic and environmental implications of replacing conventional poultry feed with insect-based feed in Kenya. J. Clean. Prod. 265, 121871.

Ahmad, I.K., Mohamed, Z.S., Amrul, N.F., Quan, C.W., Jalil, N.A.A., Basri, N.E.A., Azmi, M.R., 2021. Composting fruit and vegetable waste using black soldier fly larvae. Jurnal Kejuruteraan 33 (4), 837–843.

Allegretti, G., Talamini, E., Schmidt, V., Bogorni, P.C., Ortega, E., 2018. Insect as feed: an emergy assessment of insect meal as a sustainable protein source for the Brazilian poultry industry. J. Clean. Prod. 171, 403–412.

Banks, I., Gibson, W.T., Cameron, M.M., 2014. Growth rates of black soldier fly larvae fed on fresh human faeces and their implication for improving sanitation. Trop. Med. Int. Health 19 (1), 14–22.

Barragan-Fonseca, K.B., Dicke, M., van Loon, J.J.A., 2017. Nutritional value of the black soldier fly (*Hermetia illucens* L.) and its suitability as animal feed – a review. J. Insects as Food Feed. 3 (2), 105–120.

Barragan-Fonseca, K.Y., Barragan-Fonseca, K.B., Verschoor, G., van Loon, J.J., Dicke, M., 2020. Insects for peace. Curr. Opin. Insect Sci. 40, 85–93.

Basher, S.A., Raboy, D.G., 2018. The misuse of net present value in energy efficiency standards. Renew. Sustain. Energy Rev. 96, 218–225.

BEF, 2021. Black Soldier Fly larvae and mealworm production in a refugee setting. Africa: Bobo Eco Farm. http://www.boboecofarm.org.ug/black-soldier-fly-larvae-mealworm-production-refugee-setting/. (Accessed 10 January 2022).

Bessa, L.W., Pieterse, E., Marais, J., Hoffman, L.C., 2020. Why for feed and not for human consumption? The black soldier fly larvae. Compr. Rev. Food. Sci. F. 19, 2747–2763.

Braun, V., Clarke, V., 2006. Using thematic analysis in psychology. Qual. Res. Psychol. 3 (2), 77–101.

Bullock, N., Chapin, E., Evans, A., Elder, B., Givens, M., Jeffay, N., Pierce, B., Robinson, W., 2013. The Black Soldier Fly How-To-Guide.

Celitron, 2019. Top 6 Reasons Why Black Soldier Fly Larvae Are the Next Step in Sustainable Farming. https://celitron.com/en/blog/top-6-reasons-why-black-soldier-fly-larvae-are-the-next-step-in-sustainable-farming. (Accessed 10 January 2022).

Chen, Z.-Y., Dai, Z.-H., 2021. Application of group decision-making AHP of confidence index and cloud model for rock slope stability evaluation. Comput. Geosci. 155, 104836.

Chen, H.Y., Awasthi, S.K., Liu, T., Zhang, Z., Awasthi, M.K., 2020. An assessment of the functional enzymes and corresponding genes in chicken manure and wheat straw composted with addition of clay via metagenomic analysis. Ind. Crop. Prod. 153, 112573.

Chia, S.Y., Tanga, C.M., Ja van Loon, J., Dicke, M., 2019. Insects for sustainable animal feed: inclusive business models involving smallholder farmers. Curr. Opin. Environ. Sustain. 41, 23–30.

Čičková, H., Newton, G.L., Lacy, R.C., Kozánek, M., 2015. The use of fly larvae for organic waste treatment. Waste Manage. (Tucson, Ariz.) 35, 68–80.

Colombo, S.M., 2020. Chapter 2: physiological considerations in shifting carnivorous fishes to plant-based diets. In: Benfey, T., Brauner, C., Farrell, T. (Eds.), Fish Physiology, 38th Edition. Elsevier, pp. 53–82.

Dalalah, D., Al-Oqla, F., Hayajneh, M., 2010. Application of the analytic hierarchy process (AHP) in multi-criteria analysis of the selection of the cranes. Jordan J. Mech. Ind. 4 (5).

Diaz, R.J., Rosenberg, R., 2008. Spreading dead zones and consequences for marine ecosystems. Science 321, 926–929.

Dicke, M., 2018. Insects as feed and the sustainable development goals. J. Insects as Food Feed 4 (3), 147–156.

Dickinson, E., Harrison, M., Parker, M., Dickinson, M., Donarski, J., Charlton, A., Nolan, R., Rafat, A., Gschwend, F., Hallett, J., Wakefield, M., Wilson, J., 2019. From waste to food: optimising the breakdown of oil palm waste to provide substrate for insects farmed as animal feed. PLoS One 14 (11), e0224771.

Diener, S., Zurbrugg, C., Tockner, K., 2009. Conversion of organic material by black soldier fly larvae: establishing optimal feeding rates. Waste Manag. Res. 27, 603–610.

Dobermann, D., Swift, J.A., Field, L.M., 2017. Opportunities and hurdles of edible insects for food and feed. Nutr. Bull. 42, 293–308.

Ekins, P., Domenech, T., Drummond, P., Bleischwitz, R., Hughes, N., Lotti, L., 2019. The Circular Economy: what, Why, How and where", Background Paper for an OECD/EC Workshop on 5 July 2019 within the Workshop Series "Managing Environmental and Energy Transitions for Regions and Cities" (Paris).

English, G., Wanger, G., Colombo, S.M., 2021. A review of advancements in black soldier fly (Hermetia illucens) production for dietary inclusion in salmonid feeds. J. Agric. Food Inf. 5, 100164.

Fisher, H.J., Collins, S.A., Hanson, C., Mason, B., Colombo, S.M., Anderson, D.M., 2020. Black soldier fly larvae meal as a protein source in low fish meal diets for Atlantic salmon (*Salmo salar*). Aquaculture 521, 734978.

Freel, T.A., McComb, A., Koutsos, E.A., 2021. Digestibility and safety of dry black soldier fly larvae meal and black soldier fly larvae oil in dogs. J. Anim. Sci. 99 (3) skab407.

Fu, S.-F., Wang, D.-H., Xie, Z., Zou, H., Zheng, Y., 2022. Producing insect protein from food waste digestate via black soldier fly larvae cultivation: a promising choice for digestate disposal. Sci. Total Environ. 830, 154654.

Gao, Z., Wang, W., Lu, X., Zhu, F., Liu, W., Wang, X., Lei, C., 2019. Bioconversion performance and life table of black soldier fly (Hermetia illucens) on fermented maize straw. J. Clean. Prod. 230, 974–980.

Ghimire, L.P., Kim, Y., 2018. An analysis on barriers to renewable energy development in the context of Nepal using AHP. Renew. Energy 129, 446–456.

Gold, M., Cassar, C.M., Zurbrügg, C., Kreuzer, M., Boulos, S., Diener, S., Mathys, A., 2020. Biowaste treatment with black soldier fly larvae: increasing performance through the formulation of biowastes based on protein and carbohydrates. Waste Manag. 102, 319e329.

Grinberga-Zalite, G., Zvirbule, A., 2022. Analysis of waste minimization challenges to European food production enterprises. Emerg. Sci. J. 6 (3), 530–543.

Hanboonsong, Y., Jamjanya, T., Durst, P.B., 2013. Six-Legged Livestock: Edible Insect Farming, Collecting and Marketing in Thailand. Food and Agriculture Organization of the United Nations, Bangkok, Thailand.

Hashim, N.A., Bahri, A.R.S., Basari, N., Sharudin, N.H., 2017. Mass infestation of black soldier fly *Hermetia illucens* (Diptera: stratiomyidae) on colonies of the Indo-Malayan stingless bees *Geniotrigona thoracica* and *Heterotrigona itama*. J. Biodivers. Environ. Sci. (JBES) 2 (11), 9–15.

Higa, J.E., Ruby, M.B., Rozin, P., 2021. Americans' acceptance of black soldier fly larvae as food for themselves, their dogs, and farmed animals. Food Qual. Prefer. 90, 104119.

Ignjatijević, S., 2010. Economic aspects of production and exportation of medicinal and aromatic herbs. Zbornik radova (Fakultet za ekonomiju i inženjerski menadžment) 3, 65–79.

Ishizaka, A., Nemery, P., 2013. Multi-criteria Decision Analysis: Methods and Software. John Wiley & Sons, United Kingdom.

Ivorra, T., Hauser, M., Low, V.L., Tomberlin, J.K., Aliah, N.A.N., Cammack, J.A., Heo, C. C., 2020. *Hermetia illucens* and *Hermetia fenestrate* (Diptera: stratiomyidae) colonization of "spoiled" stingless bee *Geniotrigona thoracica* (hymenoptera: Apidae) hives in Malaysia. Insects 11, 737.

Jamaludin, M.A., Wan Khairuzzaman, M., Abdullah Sani, M.S., 2021. Black soldier fly larvae as animal feed: implications on the halal status of meat products. Halalsphere 1, 32–42.

Joly, G., Nikiema, J., 2019. Global Experiences on Waste Processing with Black Soldier fly (Hermetia Illucens): from Technology to Business. 62pCGIAR Research Program on Water, Land and Ecosystems (WLE). Resource Recovery and Reuse Series 16. International Water Management Institute (IWMI), Colombo, Sri Lanka.

Kalova, M., Borkovcova, M., 2013. Voracious larvae Hermetia illucens and treatment of selected types of biodegradable waste. Acta Univ. Agric. Silvic. Mendelianae Brunensis 61, 7.

Khaemba, C.N., Kidoido, M.M., Owuor, G., Tanga, C.M., 2021. Consumers' perception towards eggs from laying hens fed commercial black soldier fly (Hermetia illucens) larvae meal-based feeds. Processing and Products 101, 101645.

Kim, C.-H., Ryu, J., Lee, J., Ko, K., Lee, J., Park, K.Y., Chung, H., 2021. Use of black soldier fly larvae for food waste treatment and energy production in Asian countries: a review. Processes 9, 161.

Lalander, C.H., Fidjeland, J., Diener, S., Eriksson, S., Vinnerås, B., 2015. High waste-to-biomass conversion and efficient *Salmonella* spp. reduction using black soldier fly for waste recycling. Agron. Sustain. Dev. 35 (1), 261–271.

Lalander, C., Diener, S., Zurbrügg, C., Vinnerås, B., 2019. Effects of feedstock on larval development and process efficiency in waste treatment with black soldier fly (Hermetia illucens). J. Clean. Prod. 208, 211–219.

Lane, B., 2018. When Smallholder Farmers Succeed, Their Kids Go to School. https://unreasonablegroup.com/articles/smallholder-farmers-succeed-kids-go-school/. (Accessed 15 January 2022).

Leong, S.Y., Kutty, S.R.M., Malakahmad, A., Tan, C.K., 2016. Feasibility study of biodiesel production using lipids of Hermetia illucens larva fed with organic waste. Waste Manag. 47, 84–90.

Lim, J.-W., Mohd-Noor, S.-N., Wong, C.-Y., Lam, M.-K., Goh, P.-S., Beniers, J.J.A., Oh, W.-D., Jumbri, K., Ghani, N.A., 2019. Palatability of black soldier fly larvae in valorizing mixed waste coconut endosperm and soybean curd residue into larval lipid and protein sources. J. Environ. Manag. 231, 129–136.

Liu, T., Awasthi, M.K., Awasthi, S.K., Duan, Y., Zhang, Z., 2020. Effects of black soldier fly larvae (Diptera: stratiomyidae) on food waste and sewage sludge composting. J. Environ. Manag. 256.

Liu, T., Klammsteiner, T., Dregulo, A.M., Kumar, V., Zhou, Y., Zhang, Z., Awasthi, M.K., 2022. Black soldier fly larvae for organic manure recycling and its potential for a circular bioeconomy: a review. Sci. Total Environ. 833, 155122.

Madau, F.A., Arru, B., Furesi, R., Pulina, P., 2020. Insect farming for feed and food production from a circular business model perspective. Sustainability 12, 5418.

Mahmood, S., Zurbrügg, C., Tabinda, A.B., Ali, A., Ashraf, A., 2021. Sustainable waste management at household level with black soldier fly larvae (hermetia illucens). Sustainability 13, 9722.

Makkar, H.P., Tran, G., Heuzé, V., Ankers, P., 2014. State-of-the-art on use of insects as animal feed. Anim. Feed Sci. Technol. 197, 1–33.

Manurung, R., Supriatna, A., Esyanthi, R.R., Putra, R.E., 2016. Bioconversion of rice straw waste by black soldier fly larvae (Hermetia illucens L.): optimal feed rate for biomass production. J. Entomol. Zool. Stud. 4 (4), 1036–1041.

McLaren, H.J., Wong, K.R., Nguyen, K.N., Mahamadachchi, K.N.D., 2020. Covid-19 and women's triple burden: vignettes from Sri Lanka, Malaysia, Vietnam and Australia. Soc. Sci. 87 (9), 1–11.

MIDA, 2021. Palm Biomass. Malaysia: Malaysian Investment Development Authority. https://www.mida.gov.my/industries/manufacturing/food-technology/food-technology-palm-biomass/. (Accessed 8 August 2022).

Miller, A., Evans, J., Payne, C.L.R., Roberts, R., 2016. Entomophagy and power. J. Insects as Food Feed 2 (2), 121–136.

Miner, L.P., Fernandez-Bayo, J., Putri, F., Niemeier, D., Bischel, H., VanderGheynst, J.S., 2022. Predicting black soldier fly larvae biomass and methionine accumulation using a kinetic model for batch cultivation and improving system performance using semi-batch cultivation. Bioproc. Biosyst. Eng. 45 (2), 333–344.

Mohamad, L., Dina, F., Hasan, H.A., Sudesh, K., Baidurah, S., 2020. Effect of feeding strategy on the protein and fatty acid contents of black soldier fly prepupae (*Hermetia illucens*) for the potential applications as animal feed and promising alternative protein-rich food. Iop. Conf. Ser. Mat. Sci. 716, 012006.

Mohan, K., Rajan, D.K., Muralisankar, T., Ganesan, A.R., Sathishkumar, P., Revathi, N., 2022. Use of black soldier fly (*Hermetia illucens* L.) larvae meal in aquafeeds for a sustainable aquaculture industry: a review of past and future needs. Aquaculture 553, 738095.

Mohd-Noor, S.-N., Wong, C.-Y., Lim, J.-W., Mah-Hussin, M.I.A., Uemura, Y., Lam, M.-K., Ramli, A., Bashir, M.J.K., Tham, L., 2017. Optimization of self-fermented period of waste coconut endosperm destined to feed black soldier fly larvae in enhancing the lipid and protein yields. Renew. Energy 111, 646–654.

Moruzzo, R., Mancini, S., Guidi, A., 2021. Edible insects and sustainable development goals. Insects 12, 557.

Naranjo-Guevara, N., Fanter, M., Conconi, A.M., Floto-Stammen, S., 2020. Consumer acceptance among Dutch and German students of insects in feed and food. Food Sci. Nutr. 9, 414–428.

Newbold, T., et al., 2015. Global effects of land use on local terrestrial biodiversity. Nature 520, 45–50.

Nugroho, D.S., Yu-Shen, C., Chou, T.-H., Hartini, N., Chiu, H.-Y., 2019. Antifungal Lotion as value-added product for harvested BSFL processing: simple process design and economic evaluation. Jurnal Bahan Alam Terbarukan 8 (2), 124–132.

Odum, H.T., 1996. Environmental Accounting: Emergy and Environmental Decision Making.

Ong, S.-Q., Lee, B.-B., Tan, G.-P., Maniam, S., 2017. Capacity of black soldier fly and house fly larvae in treating the wasted rice in Malaysia. Malays. J. Sustain. Agric. 1 (1), 08-10.

Oonincx, D.G., de Boer, I.J., 2012. Environmental impact of the production of mealworms as a protein source for humans—a life cycle assessment. PLoS One 7, e51145.

Oppong, M., 2017. Black Soldier Fly Larvae-Based Fish Feed Production: Financial Feasibility and Acceptability Analysis. Master Thesis. The University of Ghana, Legon.

Ordonez-Araque, R., Egas-Montenegro, E., 2021. Edible insects: a food alternative for the sustainable development of the planet. Int. J. Gastron. Food Sci. 23, 100304.

Palma, L., Ceballos, S.J., Johnson, P.C., Niemeier, D., Pitesky, M., VanderGheynst, J.S., 2018. Cultivation of black soldier fly larvae on almond byproducts: impacts of aeration and moisture on larvae growth and composition. J. Sci. Food Agric. 98 (15), 5893–5900.

Palma, L., Fernández-Bayo, J., Putri, F., VanderGheynst, J.S., 2020. Almond by-product composition impacts the rearing of black soldier fly larvae and quality of the spent substrate as a soil amendment. J. Sci. Food Agric. 100, 4618–4626.

Parodi, A., De Boer, I.J.M., Gerrits, W.J.J., Van Loon, J.J.A., Heetkamp, M.J.W., Schelt, J. V., Bolhuis, J.E., Van Zanten, H.H.E., 2020. Bioconversion efficiencies, greenhouse gas and ammonia emissions during black soldier fly rearing - a mass balance approach. J. Clean. Prod. 271, 122488.

Perednia, D.A., Anderson, J., Rice, A.A., 2017. Comparison of the greenhouse gas production of black soldier fly larvae versus Aerobic microbial decomposition of an organic feed material. J. Ecol. Environ. 5 (3), 10–16.

Pleissner, D., Smetana, S., 2020. Estimation of the economy of heterotrophic microalgae- and insect-based food waste utilization processes. Waste Manag. 102, 198–203.

Rahman, H.A., 2018. Climate change scenario in Malaysia: engaging the public. Int. J. Malay-Nusantara Stud. 2 (1), 55–77.

Raksasat, R., Lim, J.W., Kiatkittipong, W., Kiatkittipong, K., Ho, Y.C., Lam, M.K., Font-Palma, C., Mohd Zaid, H.F., Cheng, C.K., 2020. A review of organic waste enrichment for including palatability of black soldier fly larvae: wastes to valuable resources. Environ. Pollut. 267, 115488.

Raksasat, R., Abdelfattah, E.A., Liew, C.S., Rawindran, H., Kiatkittipong, K., Mohamad, M., Mohd Zaid, H.F., Jumbri, K., Lam, M.K., Lim, J.W., 2022. Enriched sewage sludge from anaerobic pre-treatment in spurring valorization potential of black soldier fly larvae. Environ. Res. 212, 113447.

Ravi, H.K., Degrou, A., Costil, J., Trespeuch, C., Chemat, F., Vian, M.A., 2020. Larvae mediated valorization of industrial, agriculture and food wastes: biorefinery concept through bioconversion, processes, procedures, and products. Processes 8, 857.

Reed, M.S., Graves, A., Dandy, N., Posthumus, H., Hubacek, K., Morris, J., Prell, C., Stringer, L.C., Quinn, C.H., 2009. Who's in and why? A typology of stakeholder analysis methods for natural resource management. J. Environ. Manag. 90, 1933–1949.

Roffeis, M., et al., 2018. Life cycle cost assessment of insect based feed production in West, Africa. J. Clean. Prod. 199, 792–806.

Ruby, M.B., Rozin, P., 2019. Disgust, sushi consumption, and other predictors of acceptance of insects as food by Americans and Indians. Food Qual. Prefer. 74, 155–162.

Saaty, R.W., 1987. The analytic hierarchy process-what it is and how it is used. Mat. Model. 9 (3), 161–176.

Salomone, R., Saija, G., Mondello, G., Giannetto, A., Fasulo, S., Savastano, D., 2017. Environmental impact of food waste bioconversion by insects: application of Life Cycle Assessment to process using Hermetia illucens. J. Clean. Prod. 140, 890–905.

Sarpong, D., Oduro-Kwarteng, S., Gyasi, S.F., Buamah, R., Donkor, E., Awuah, E., Baah, M.K., 2019. Biodegradation by composting of municipal organic solid waste into organic fertilizer using the black soldier fly (*Hermetia illucens*) (Diptera: stratiomyidae) larvae. Int. J. Recycl. Org. Waste Agric. 8 (Suppl. 1), S45–S54.

Saucier, L., M'ballou, C., Ratti, C., Deschamps, M.-H., Lebeuf, Y., Vandenberg, G.W., 2021. Comparison of black soldier fly larvae pre-treatments and drying techniques on the microbial load and physico-chemical characteristics. J. Insects as Food Feed. 8 (1), 45–64.

Searchinger, T., Waite, R., Hanson, C., Ranganathan, J., Matthews, E., 2013. Creating a sustainable food future. A menu of solutions to sustainably feed more than 9 billion people by 2050. World resources report 2013-14 : interim findings 1–556.

Setti, L., Francia, E., Pulvirenti, A., Gigliano, S., Zaccardelli, M., Pane, C., Caradonia, F., Bortolini, S., Maistrello, L., Ronga, D., 2019. Use of black soldier fly (Hermetia illucens (L.), Diptera: stratiomyidae) larvae processing residue in peat-based growing media. Waste Manage. (Tucson, Ariz.) 95, 278–288.

Shumo, M., Osuga, I.M., Khamis, F.M., Tanga, C.M., Fiaboe, K.K.M., Subramanian, S., Ekesi, S., Huis, A.v., Borgemeister, C., 2019. The nutritive value of black soldier fly larvae reared on common organic waste streams in Kenya. Sci Rep-UK 9, 10110.

Siddiqui, S.A., Ristow, B., Rahayu, T., Putra, N.S., Yuwono, N.W., Nisa', K., Mategeko, B., Smetana, S., Saki, M., Nawaz, A., Nagdalian, A., 2022. Black soldier fly larvae (BSFL) and their affinity for organic waste processing. Waste Manage. (Tucson, Ariz.) 140, 1–13.

Sinha, K.C., Labi, S., 2007. Transportation Decision Making: Principles of Project Evaluation and Programming. Wiley, Hoboken, New Jersey.

SNRD Africa, 2021. Women's Empowerment: Going beyond Business as Usual in Rural Development. Africa: Sector Network Rural Development. https://www.snrd-africa.net/measuring-empowerment-correctly/. (Accessed 16 January 2022).

Spartano, S., Grasso, S., 2021. UK consumers' willingness to try and pay for eggs from insect-fed hens. Future Foods 3, 100026.

Sprangers, T., Ottoboni, M., Klootwijk, C., Ovyn, A., Deboosere, S., 2017. Nutritional composition of black soldier fly (Hermetia illucens) prepupae reared on different organic waste substrates: nutritional composition of black soldier fly. J. Sci. Food Agric. 97, 2594–2600.

Stamer, A., Wesselss, S., Neidigk, R., Hoerst-Schwark, G., 2014. In: Rahmann, G., Aksoy, U., Istanbul (Eds.), Black Soldier Fly (Hermetia Illucens) Larvae-Meal as an Example for a New Feed Ingredients' Class in Aquaculture Diets Proceedings of the 4th ISOFAR Scientific Conference, pp. 1043–1046.

Stockholm, 2015. High Value Organic Waste Treatment via Black Soldier Fly Bioconversion. Royal Institute of Technology.

Szendrő, K., Nagy, M.Z., Tóth, K., 2020. Consumer acceptance of meat from animals reared on insect meal as feed. Animals 10, 1312.

THP, 1994. What Constitutes an Enabling Environment for the Poor to Succeed in Their Own Development? Bangladesh: the Hunger Project. https://advocacy.thp.org/1994/04/enabling-environment/. (Accessed 1 February 2022).

TRF, 2020. Nourish People and Planet. *Black Soldier Flies: Inexpensive And Sustainable Source For Animal Feed.* US. The Rockefeller Foundation. https://www.rockefellerfoundation.org/case-study/black-soldier-flies-inexpensive-and-sustainable-source-for-animal-feed/. (Accessed 1 February 2022).

Umana, U.S., Ebong, M.S., Godwin, E.O., 2020. Biomass production from oil palm and its value chain. J. Human, Earth, and Future 1 (1), 30–38.

UNFCCC, 2015. Intended Nationally Determined Contribution of the Government of Malaysia. United Nations Framework Convention on Climate Change, Malaysia.

Vaismoradi, M., Turunen, H., Bondas, T., 2013. Content analysis and thematic analysis: implications for conducting a qualitative descriptive study. Nurs. Health Sci. 15 (3), 398–405.

van Huis, A., Oonincx, D.G.A.B., Rojo, S., Tomberlin, J.K., 2020. Insects as feed: house fly or black soldier fly? J. Insects as Food Feed 6 (3), 221–229.

Velenturf, A.P.M., Purnell, P., Macaskie, L.E., Mayes, W.M., Sapsford, D.J., 2019. A new perspective on a global circular economy. In: Resour. Recovery from Wastes: Towards Circular Econ. Roy. Soc. Chem. 1–22.

Vermeulen, S.J., Campbell, B.M., Ingram, J.S.I., 2012. Climate change and food systems. Annu. Rev. Environ. Resour. 37, 195–222.

Vilela, J.d.S., Andronicos, N.M., Kolakshyapati, M., Hilliar, M., Sibanda, T.Z., Andrew, N. R., Swick, R.A., Wilkinson, S., Ruhnke, I., 2021. Black soldier fly larvae in broiler diets improve broiler performance and modulate the immune system. Animal Nutrition 7, 695–706.

Wada, Y., van Beek, L.P.H., van Kempen, C.M., Reckman, J.W.T.M., Vasak, S., Bierkens, M.F.P., 2010. Global depletion of groundwater resources. Geophys. Res. Lett. 37, L20402.

Walter, A., Klammsteiner, T., Gassner, M., Heussler, C.D., Kapelari, S., Schermer, M., Insam, H., 2020. Black soldier fly school workshops as means to promote circular economy and environmental awareness. Sustainability 12, 9574.

Wang, Y.-S., Shelomi, M., 2017. Review of black soldier fly (*Hermetia illucens)* as animal feed and human food. Foods 6 (91), 1–23.

Wang, H., ur Rehman, K., Liu, X., Yang, Q., Zheng, L., Li, W., Cai, M., Li, Q., Zhang, J., Yu, Z., 2017. Insect biorefinery: a green approach for conversion of crop residues into biodiesel and protein. Biotechnol. Biofuels 10, 304.

Xiao, X., Jin, P., Zheng, L., Cai, M., Yu, Z., Yu, J., Zhang, J., 2018. Effects of black soldier fly (Hermetia illucens) larvae meal protein as a fishmeal replacement on the growth and immune index of yellow catfish (Pelteobagrus fulvidraco) Aquac. Res. 49, 1569–1577.

Yoon, C.-H., Jeon, S.-H., Ha, Y.J., Kim, S.W., Bang, W.Y., Bang, K.H., Gal, S.W., Kim, L.-S., Cho, Y.-S., 2020. Functional chemical components in Protaetia brevitarsis larvae: impact of supplementary feeds. Food Sci. Anim. Resour. 40, 461–473.

Zhou, F., Tomberlin, J.K., Zheng, L., Yu, Z., Zhang, J., 2013. Developmental and waste reduction plasticity of three black soldier fly strains (Diptera: stratiomyidae) raised on different livestock manures. J. Med. Entomol. 50, 1224–1230.

Zozo, B., Wicht, M.M., Mshayisa, V.V., Wyk, J.v., 2022. The nutritional quality and structural analysis of black soldier fly larvae flour before and after defatting. Insects 13, 168.