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Black soldier fly larvae (BSFL) and their affinity for organic waste processing

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ABSTRACT

There are two major problems that we are facing currently. Firstly, a growing human population continues to contribute to the increased food demand. Secondly, the volume of organic waste produced will threaten human health and the quality of the environment. Recently, there is an increasing number of efforts placed into farming insect biomass to produce alternative feed ingredients. Black soldier fly larvae (BSFL), *Hermetia illucens* have proven to convert organic waste into high-quality nutrients for pet foods, fish and poultry feeds, as well as residue fertilizer for soil amendment. However, better BSFL feed formulation and feeding approaches are necessary for yielding a higher nutrient content of the insect body, and if performed efficiently, whilst converting waste into higher value biomass. Lastly, this paper reveals that BSFL, in fact, thrives in various ranges of organic matter composition and with simple rearing systems.

1. Introduction

The persistent increase in organic wastes generated worldwide is regarded as an emerging threat not only to human health but also to biodiversity and the ecosystem. Environmental concerns associated with this overwhelming level of waste, include contamination of water, air, and soil (Pastor et al., 2015), and can also be a route of spreading pathogens (Kawasaki et al., 2020; Pastor et al., 2015; Tanga et al., 2021; Wynants et al., 2019). Moreover, food waste was reported to cause detrimental impacts on the environment by the methane gas emitted from landfills (FAO, 2014). Organic wastes are commonly treated using landfilling, composting, or incineration (Kim et al., 2021; Kinasih et al., 2020). However, there are several drawbacks linked with landfill disposal, such as the occupation of valuable space taken up by wastes, the spread of pathogenic organisms, production of undesirable odors as well as contribution to greenhouse gas emissions (FAO, 2013). Furthermore, these commonly used waste management methods require large periods of time before the wastes are fully decomposed (Chun et al., 2019).

Although the aforementioned means of waste treatment are commonly used in many cities within developing countries, the lack of interest to invest in methods to gather, separate, and process the organic wastes delays addressing the issue of the steadily increasing amounts of organic wastes (Kinasih et al., 2020). More sustainable methods are

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required to solve the waste accumulation problem efficiently. Numerous studies have underlined the use of black soldier fly (*Hermetia illucens*) larva as the best candidate for processing organic wastes (Kinasih et al., 2018; Lalander et al., 2019; Mahmood et al., 2021; Shumo et al., 2019a, 2019b). Even though the potential role of black soldier fly (BSF) in organic waste treatment was previously reviewed by various researchers (da Silva and Hesselberg, 2020; Kim et al., 2021; Pastor et al., 2015; Purkayastha and Sarkar, 2021; Raksasat et al., 2020; Singh and Kumari, 2019; Surendra et al., 2020), there is still a lack of systemized knowledge about the potential of *H. illucens* for the waste treatment.

The use of insects, including BSF, is well known for playing a vital role in solving issues linked with high volumes of organic wastes distributed all over the world. It has progressively been employed in treating biological waste as it is seen as being an environmentally friendly and inexpensive process (Kim et al., 2021; Singh and Kumari, 2019). The crucial role of BSF larvae (BSFL) in recycling biological wastes received more attention in past decades (Lu et al., 2021). BSFL was highlighted as potent recyclers of various types of wastes such as abattoir waste, food waste, fruits and vegetable waste, and human feces (Lalander et al., 2019). BSF falls into the Diptera family from the order Stratiomyidae and inherently resides in temperate tropical areas (Singh and Kumari, 2019). In a study conducted by Ibadurrohman et al. (2020), BSFL was noticed to have a remarkable ability (75%) of recycling the biological wastes in which 800 g of larval biomass would be produced from 4 kg of waste.

To optimize its bioconversion efficacy, BSFL must be maintained under ideal environmental conditions, including parameters such as humidity, nutrient composition, physical properties, temperature, and oxygen level (Diener et al., 2011a; Lu et al., 2021; Purkayastha and Sarkar, 2021; Singh and Kumari, 2019). Amongst rearing conditions, the temperature was recognized to play a significant role in the growth of BSFL in which the optimal temperature ranges between 25 °C and 30 °C (Shumo et al., 2019a). Furthermore, the type of food substrate is quite essential for optimized bioconversion activity of BSFL (Fadhillah and Bagastyo, 2020; Nyakeri et al., 2017; Sanjaya et al., 2019; Shumo et al., 2019b; Tanga et al., 2021; Wang et al., 2020). Like other living organisms, BSFL needs nutrients to support their growth. Therefore, for higher bioconversion performance, BSFL needs to feed on the organic wastes rich in digestible nutritive substances (Kinasih et al., 2020; Leong and Kutty, 2020). In addition, it was stressed that BSFL can effectively decompose various types of organic waste if it contains an adequate amount of protein and carbohydrates (Lalander et al., 2019; Lu et al., 2021). However, the growth is hindered when BSFL is fed on some nutrients-deficient organic waste. Nevertheless, it is interestingly reported that the BSFL optimized growth and development could be promoted if nutrient-deficient wastes are fortified with cheap high-nutritive substrates, such as soybean curd residues (Raksasat et al., 2020).

1.1. Significance of BSFL in organic waste management

BSFL is reported in numerous studies for playing a great role in organic waste management (Czekała et al., 2020; da Silva and Hesselberg, 2020; Fadhillah and Bagastyo, 2020; Purkayastha and Sarkar, 2021) and valorization of various biodegradable wastes (Adebayo et al., 2021; Chun et al., 2019; Kawasaki et al., 2020; Leong et al., 2016; Nyakeri et al., 2017; Pastor et al., 2015; Spranghers et al., 2017). The larval biomass generated through bioconversion of organic wastes is discovered to be a high-quality source of fat/oil (Kim et al., 2021; Leong et al., 2015; Lu et al., 2021; Tanga et al., 2021) as well as proteins (Kinasih et al., 2020; Nyakeri et al., 2017; Shumo et al., 2019b), and is increasingly applied in multiple industries for animal feeding, biodiesel production, biopolymers (chitin), and soil composting (Purkayastha and Sarkar, 2021).

It is noteworthy that whole or processed BSF larvae or pupae can be incorporated into the diets of poultry, fish, pets, and pigs thereby serving as prospective alternatives of common feed ingredients namely soybean- and fish-based meal (Surendra et al., 2020). Consequently, the usual feed ingredients, which insect products could replace, can be reserved for other uses including human consumption thus contributing to food security. Furthermore, the bioactive chemicals, such as antimicrobial peptides, present in BSFL could also add great benefits to animal diets (Surendra et al., 2020). However, in a review done by Wynants et al. (2019), it is emphasized that special attention should be given to the rearing of the BSFL since pathogenic organisms such as *Salmonella* sp. and *Bacillus cereus* can be detected in larvae and/or residue samples and carried through to the animals they are being fed to. In this case, the authors recommend employing suitable decontamination technologies (Wynants et al., 2019).

BSFL-based fats are revealed to be the potential non-food raw materials for making biodiesel as the properties of the BSFL-based fuel were found comparable to those of standard biodiesel made from rapeseed oil (Li et al., 2011). Besides contributing to food security, the use of low-cost non-food feedstock for biodiesel production has been recognized as an affordable environmentally friendly fuel.

The main objective of this review article was to collect state-of-the-art knowledge about the benefits of rearing BSFL on organic waste as a viable alternative to harvested grains and other raw materials already used in livestock feed. This concept of utilizing low value inputs to create value-added products out of BSFL biomass is the core of the review and wishes to highlight the need to prioritize more sustainable and economic methods of feeding farmed BSFL. The focus was on the economic benefits of the production system itself and the benefits of BSFL as a product. We also reviewed the present status of the industry, the research gaps and challenges, and the future perspective of the BSFL-based organic waste treatment technology. The current review is aimed to systemize and analyze the recent literature on the application of BSFL for the treatment of different waste types.

2. The benefits of using BSFL for biowaste conversion

The inadequate management of organic waste causes water and air pollutions and yields no valuable by-products such as protein, oil, or frass (excreta of insects in the larval stage). Hence, the use of insects to manage organic waste has become a great potential and gained more attention in the past years (Lalander et al., 2015). Mealworms, common houseflies, and BSF are currently some of the most extensively studied insects in organic waste conversion and could serve as alternative protein sources for animal feed (van Huis et al., 2020). The larvae of these insects, particularly BSFL, are voracious eaters of decaying organic matter, hence they have been successfully used to reduce waste streams including livestock (chicken, cow, swine, etc) manure, human excreta, poultry slaughterhouse waste, mill by-products, food waste, fruits, and vegetable waste, as well as palm oil industry waste (Palm Kernel Expeller) (Beskin et al., 2018; Gold et al., 2020a; Lalander et al., 2019; Raksasat et al., 2021).

The potential of BSFL to process organic waste has gained more attention than the other fly species. In modern society, BSF offers a solution to solve challenges to the lack of global waste management, unemployment in urban areas, and increased demand for sustainable animal feed (Dortmans et al., 2021). The benefits of using BSF in organic waste conversion from the perspective of waste managers (environmental and functional health benefits) are potentially waste reduction in a short time; low carbon footprint; high conversion of feed to body mass; being a non-disease vector species; as well as reducing pathogen and others pest populations. Then from the perspective of businesses, it produces valuable materials economically whilst requiring low water and land usage compared to other alternative protein sources. Moreover, Beskin et al. (2018) demonstrated the ability of BSFL to reduce the odorous compounds from poultry, swine, and dairy manures up to 87% or more. Hence proving an additional benefit of using BSFL as an environmentally friendly method in managing livestock manure compared to current conventional methods. All of the above attributes make BSF an attractive remediation technology to convert biowaste into high-quality products. To summarize, Bortolini et al. (2020) reported that these benefits of the BSF system make it fits well in a circular economy, due to the profitability of the processing decaying organic matter into larval biomass and to the absence of the residue at the end of the process, because the frass as residue from the BSF system, could be put back into the system to provide compost-like properties as a soil enhancer.

2.1. High conversion capacity and high-quality products

The use of BSFL in a bioconversion system appears to be more effective and works better than composting. That is in terms of organic waste reduction in a shorter amount of time and resulted in high-quality products for agricultural uses if bioconversion is done in favorable conditions, e.g. temperatures 27–30 °C; 70–85% humidity; shaded environment; and optimal food supply) (Dortmans et al., 2021; Holmes et al., 2012; Tomberlin et al., 2002a, 2009). Waste reduction and bioconversion rate are commonly used as indicators to determine the efficiency of the type of waste treated by BSFL (Gold et al., 2020a; Lalander et al., 2019). Waste reduction is a value on a dry mass basis that is calculated from a difference between feed provided and residue then divided by feed provided during the experiment, whereas bioconversion rate (usually in dry mass) is calculated by dividing larvae weight gain (the final larval weight reduced by initial larval weight) with the total feed provided (Gold et al., 2020a)

The bioconversion rate depends on many factors, e.g. feed composition (amounts of digestible nutrients, pH, and moisture content) and feeding rates (Banks et al., 2014). Meanwhile, the density of the larvae (per volume of conversion unit) and feeding regime (type, amount, frequency, and nutritional content) have a great effect on the conversion process of organic waste (Banks et al., 2014; Dortmans et al., 2021). The ideal moisture content of food for BSFL is in the range of 70–80%, whereas, the lower threshold of that is likely between 40 and 55% (Bortolini et al., 2020; Dortmans et al., 2021; Ermolaev et al., 2019; Furman et al., 1959; Lalander et al., 2015; Newton et al., 2005a). The availability of digestible carbon and the high protein content also greatly contribute to biomass yield value (Dortmans et al., 2021; Lalander et al., 2019). Gold et al. (2020a) further added that besides pH and moisture content of substrate fed to BSFL, nutrient composition of the substrate [e.g. protein, non-fiber carbohydrate (NFC), fiber (cellulose & lignin, hemicellulose), lipids, protein: NFC ratio, and caloric content] also influence the performance of waste treatment and larval biomass production efficiency.

Table 1 showed that BSFL can reduce organic waste significantly by up to 84.8% and a high waste-to-biomass conversion rate of 27.9%. In comparison to poultry feed bioconversion, BSFL rearing on municipal organic waste, food waste-1, and feed formulations of F4 and F8 have similar results in terms of waste reduction. Whereas human feces-1, F3, and F10 were reduced more efficiently with BSFL (73.0–84.8%) than that of poultry feed. BSF bioconversion had similar results to bioconversion on poultry feed when grown on human feces-2, human feces-4, vegetable canteen waste, and feed formulations of F5 and F7, while it was more beneficial on food waste-2 and feed formulations of F4 and F8. To summarize, the use of F4 and F8 in BSFL feed results in a higher bioconversion rate and waste reduction than in cases with others. According to Gold et al. (2020a), two indicated feeds have higher lipid content (19.0 and 22.3%, respectively) and lower fiber content (38.5 and 39.8%, respectively) than other formulations. Overall, using a formulation by mixing different types of waste could significantly increase performance parameters (i.e. waste reduction and bioconversion) compared to provide individual waste.

The efficiency of organic waste management with BSFL can be increased by mixing various waste streams to compensate limitations of separate streams (Ermolaev et al., 2019). By doing that, the bioconversion rate of the waste streams that contain low protein could be

Table 1
Comparison of the waste reduction and bioconversion rates by black soldier fly larvae (BSFL) on various substrates in comparison to chicken feed bioconversion.

Substrate	Waste reduction (%)	Bioconversion rate (%)	References
Individual wastes			
Abattoir waste	46.3	15.2	Lalander et al. (2019)
Canteen waste	37.9	15.3	Gold et al. (2020a)
Cow manure	12.7	3.8	Gold et al. (2020a)
Digested sludge	13.2	0.2	Lalander et al. (2019)
Food waste-1	66.7	7.7	Salomone et al. (2017)
Food waste-2[*]	52.3	27.9	Ermolaev et al. (2019)
Food waste-3	55.3	13.9	Lalander et al. (2019)
Fruits and vegetable	46.7	4.1	Lalander et al. (2019)
Human feces-1	73.0	NA	Lalander et al. (2013)
Human feces-2	45.8	22.9	Banks et al. (2014)
Human feces-3	47.7	11.3	Lalander et al. (2019)
Human feces-4	43.9	20.7	Gold et al. (2020a)
Municipal organic waste	68.0	11.8	Diener et al. (2011a)
Poultry manure	60.0	7.1	Lalander et al. (2019)
Poultry slaughterhouse waste	30.7	13.4	Gold et al. (2020a)
Primary sludge	63.3	2.3	Lalander et al. (2019)
Swine manure	56.0	NA	Newton et al. (2005a)
Undigested sludge	49.2	2.2	Lalander et al. (2019)
Vegetable canteen waste	58.4	22.7	Gold et al. (2020a)
Waste formulations			
F1[a]	55.1	11.8	Lalander et al. (2015)
F2[b]	61.1	14.2	Lalander et al. (2019)
F3[c]	75.7	NA	Bortolini et al. (2020)
F4[d]	64.1	31.8	Gold et al. (2020a)
F5[e]	51.1	20.9	Gold et al. (2020a)
F6[f]	47.2	15.5	Gold et al. (2020a)
F7[g]	58.3	22.9	Gold et al. (2020a)
F8[h]	65.2	30.9	Gold et al. (2020a)
F9[i]	56.6	19.8	Gold et al. (2020a)
F10[j]	84.8	1.3	Raksasat et al. (2021)
Poultry feed (benchmark)[**]	67.7	21.0	Gold et al. (2020a)

[*] Note: NA = not available, DM = dry mass; Associated bacteria and larvae (a spore-forming bacteria consortium isolated from the gut of BSF larvae) were added to the substrate at the start of the conversion process.

[**] UFA 625 (UFA AG, Switzerland).

[a] 40% swine manure, 40% dog food, and 20% human feces.

[b] 50% abattoir waste and 50% fruits & vegetable waste.

[c] 34.5% chicken manure, 58.3% water and 7.2% coarse chabazite.

[d] 23% mill by-products, 16% human feces, 11% cow manure, and 50% vegetable canteen waste.

[e] 37% mill by-products, 7% canteen waste, 35% cow manure, and 21% vegetable canteen waste.

[f] 51% mill by-products, 14% human feces, and 34% cow manure.

[g] 60% mill by-products, 20% canteen waste, and 20% human feces.

[h] 33% mill by-products, 33% canteen waste, and 33% vegetable canteen waste.

[i] 65% mill by-products, 22% poultry slaughterhouse waste, and 12% cow manure.

[j] 20% sewage sludge and 80% palm kernel expeller (PKE).

increased, and the treatment duration decreased. Gold et al. (2020a) also have a similar perspective that mixing various waste streams to feed BSFL results in the survival rate up to 97–100% in comparison to the individual waste. However, practically formulating different organic waste types and maintain their macronutrients within ideal ranges, would be quite difficult in the operations of BSFL treatment facilities.

An increase in poultry production numbers globally calls for the improvement in poultry manure management methods. In poultry farms, the accumulation of manure could be reduced by up to 60% via feeding to BSFL (see Table 1). Further, the larvae can reduce the amount of chicken manure up to 56% and convert it into biomass high in protein and fat that may serve as animal feed, even more, it could increase the net revenue of layer house by about $25,000 yearly (Newton et al., 2005a). A similar result also showed an average of 52% substrate reduction and 28% bioconversion ratio (both dry matter basis) on food waste during 14 days of the experiment (Ermolaev et al., 2019). Although BSFL could reduce the waste amount, it is still an issue for food consumption because of food safety issues (Smetana et al., 2016). Therefore, BSF is perceived more for feed purposes rather than as food consumption.

Besides producing larval frass usable as a soil enhancer, another product from BSFL treatment is chitin. Chitin is a major substance forming the exoskeleton of arthropods, including insects. Many applications for chitin are highly possible and have been available in the market, for example, it is used as a surgical suture, edible film, binder, and chitosan (Nagdalian et al., 2018; Surendra et al., 2020). Even though, insect-based chitin is a new area for research and development (Veldkamp et al., 2012). Additionally, BSFL not only consumes good quality waste streams but also shows the antibiotic response to inhibit the growth of pathogenic bacteria (PB) (Awasthi et al., 2020).

2.2. Production with low carbon footprint

Biowaste (municipal solid waste from the household kitchen and food waste, market waste, park waste, and processing residue from food manufacturing plants) makes up as much as 70% of the waste in low- and middle-income areas and generally ends up in landfills and wastewater which account for around 90% of the global waste sector emissions (Mertenat et al., 2019). The emissions of Greenhouse gases (GHGs) such as methane (CH_4), ammonia (NH_3), and nitrous oxide (N_2O) are high environmental concerns for humans and climate, and those gases result from material decomposing in landfills. By diverting this biowaste to feed BSFL in mass production, the alternative of using the landfills is avoided as well as comparing the cost of creating raw materials equivalent to that of BSF protein meal and BSF oils, means the opportunity to improve efficiency in sustainability for the end-products is doubled (Fig. 1). A case study in Indonesia shows that the BSF waste treatment facility has lower hazardous gas emissions (CO_2, CH_4, and N_2O) and energy consumption (electricity and diesel) than the open windrowing composting (Mertenat et al., 2019). Then, the heat map study by Awasthi et al. (2020) reveals that the BSFL application has a positive correlation with the temperature, pH, C/N ratio, gaseous, and PB population. Besides that, according to Smetana et al. (2016), the insect-based protein meal is 2–5 times more environmentally friendly product compared to the products commercially available.

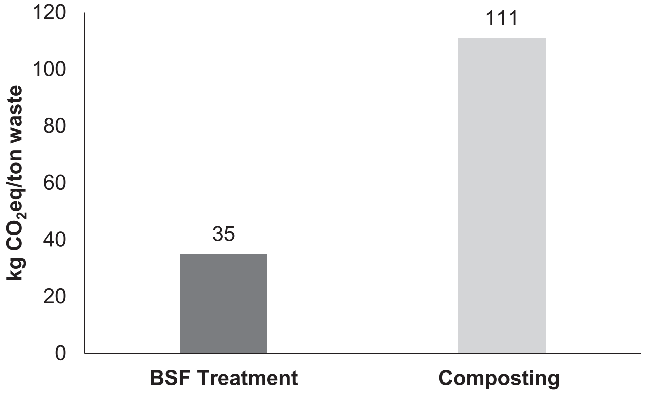

Fig. 1. Summary of Global Warming Potential (GWP) per ton biowaste (ww) expressed in kg CO_2eq from direct, indirect, and avoided emissions of BSF treatment and composting. Adapted from Mertenat et al, (2019).

The bioconversion process with BSFL shows a lower Global Warming Potential (GWP) compared to protein sources from soybean meal or lipids from rapeseed (Li et al., 2011; Pimentel et al., 2004). In terms of the substitution of N fertilizer by a compost produced from larval frass and soybean meal by BSF protein (dried BSF or BSF meal), a lower carbon footprint might be achieved (Salomone et al., 2017). A similar perspective is also shared by Ermolaev et al. (2019) that the direct GHG emission (CH_4 and N_2O) from BSFL treatment is relatively low over 11 days of treatment. Also, no NH_3 emissions are detected. Therefore, BSFL treatment offers an environmentally friendly alternative method with high GWP reduction and low direct GHG emissions than conventional organic waste treatment.

2.3. Not vectors of disease

The flies attracted by food are generally capable to transmit pathogenic microorganisms. The presence of a common house fly, is a nuisance to residences and businesses nearby any accumulated and untreated organic waste. Such pest flies are being the primary subject of the fly management and control programs (Axtell and Arends, 1990). The operation of a BSF facility does not entail crucial hazards to human health, compared to other fly species (Dortmans et al., 2021). The BSF adults have a short life and do not feed as they have redundant mouthparts (Axtell and Arends, 1990; Dortmans et al., 2021; Sheppard et al., 2002).

The adults of BSF are not coming near to human habitats or human foods and survive primarily on the energy stored in the fat body during the larval stage (Sheppard et al., 2002; van Huis et al., 2013b, 2020). To date, no reported data indicate BSF as a vector of diseases (van Huis et al., 2020). Large storage of fat provided by the larvae reduces or eliminates the necessity of adults to feed and spread any potential disease (Furman et al., 1959; Sheppard et al., 2002; van Huis et al., 2013b, 2020). Compared to BSF, house fly seems to be more likely to transmit diseases. Thus, the legislation may favor BSF than the house fly, which might be a great issue in case using manures and feces as substrates for feeding BSFL (van Huis et al., 2020).

2.4. Reduce pathogen and other vermin on decaying matter

Diarrhea caused by infection of disease agents (for example *Clostridium difficile* on manures) generally spreads throughout low- and middle-income countries. Inadequate sanitation becomes a significant factor in to spread of such diseases. The manure of livestock animal and human activities is the most waste contributed to the sanitation, for example, the pollution of groundwater and GHG emissions, agricultural contamination, and spreading of diseases, e.g. diarrhea and cholera

(Awasthi et al., 2020; Lalander et al., 2013). Furthermore, the phylum of Proteobacteria is one of the most PB reported nowadays, besides phyla of Firmicutes, Actinobacteria, and Bacteroidetes. *Escherichia* sp., *Salmonella* sp., *Vibrio* sp., and *Yersinia* sp., which were generally correlated with many infectious diseases, are examples of genera from the Proteobacteria phylum. Interestingly, BSFL has an exceptional potency to reduce the indigenous PB (e.g. *Escherichia* sp., *Salmonella* sp.) and make the end product arrive as matured compost can meet the requirements to be used as fertilizer and/or soil improver (Awasthi et al., 2020).

The feeding activity of BSFL could reduce and/or inactivate pathogenic microorganisms significantly, such as *E. coli* and *Salmonella* sp. in alkaline chicken manure at warm temperature (27–32 °C) (Erickson et al., 2004) and *Salmonella* sp. on human feces over eight days (see Table 2). The antimicrobial activity of larvae is reported only under alkaline conditions. Despite this, the risk reduction of disease transmission is achieved through high waste reduction as opposed to pathogen inactivation/reduction (Dortmans et al., 2021; Erickson et al., 2004; Lalander et al., 2013; van Huis et al., 2020). A similar result was also reported by Lalander et al. (2015) that a reduction of *Salmonella* spp. concentration revealed on swine manure and food waste were noticed over 14 days, even below the detection limit over 5 weeks (see Table 2). A recent study confirmed that BSFL applied on chicken and cow manure significantly has a greater reduction of PB (90–93%) that was noticed within 9 days, while *Salmonella* sp. was absent, then reduction of PB was noticed also by 86–88% on pig manure and sewage sludge (Awasthi et al., 2020). Previous studies showed that temperature and the amount of manure provided significantly impact the ability of BSFL to reduce *E. coli* with the greatest inhibition at 27 °C on dairy manure (Liu et al., 2008). On the other hand, the type and pH of manure significantly affected the survival and the growth of *E. coli*, hence, bacteria reproduction most likely could be inhibited if pH levels of the manures were outside an ideal range for PB to grow (Erickson et al., 2004; Liu et al., 2008).

The interspecific competition between house fly and BSF could be activated through the feeding activity of BSFL (with a sufficient number of larvae) to lower the development of house flies. The house fly is rarely found in manure colonized by BSFL (Axtell and Arends, 1990; Furman et al., 1959; Newton et al., 2005a; Sheppard, 1983). Although the development and survival rate of both species are affected by the age of food, moisture and nutritional contents of the food, and the amount and frequency of food provided, yet, it has a greater impact on BSFL than that on house fly (Dortmans et al., 2021; Miranda et al., 2019). Other studies also supported the fact that BSFL could repel common houseflies and *Fannia* sp. populations on poultry manure (Axtell and Arends, 1990; Sheppard, 1983). Meanwhile, Bradley and Sheppard (1984) confirmed that the presence of chemical communication (allomone) is believed to be present in inhibiting the oviposition of house flies by avoiding habitats that are already infested by BSFL in a dense population optimally. Even though, both chemical and physical factors may be acting together to repel the oviposition activity of house flies. Therefore, proving that BSF is a natural competitor of house fly infestation, and could be used as a strategy to manage the population of disease-vector flies such as the common house fly in poultry manure.

Table 2
The effect of the Black soldier fly larvae fed by different substrates on population reduction of *Escherichia coli* and *Salmonella* spp.

Pathogenic bacteria	Reduction (log CFU/g)*	Duration	Substrate
Escherichia coli	>6.0	3 days	Dairy manure[a]
Escherichia coli O157:H7	>7.0	3 days	Chicken manure[b]
Salmonella spp.	5.5	4 days	Chicken manure[b]
Salmonella spp.	6.0**	8 days	Faecal sludge[c]
Salmonella spp.	>7.0**	5 weeks	Swine manure, dog food, and human feces[d]

[*] Note: With an average initial bacteria inoculation was 7 log CFU/g, except on fecal sludge was 5 log CFU/g.

[**] Below detection limit.

[a] Liu et al. (2008).

[b] Erickson et al. (2004).

[c] Lalander et al. (2013).

[d] Lalander et al. (2015).

2.5. Low water and land usage compared with other alternative protein sources

Currently, the main protein sources in animal feed are produced from soybean and fish meals. However, the decreased availability of fish stocks used for fish meal, caused by overfishing and the reduction of land and water resources, is increasing the import activities to meet the demand. Besides, fish meal production is a significant contributor to over-fishing. Accordingly, sustainable farming requires advanced solutions to meet the demand of feed animals (DiGiacomo and Leury, 2019; Dortmans et al., 2021; van Huis et al., 2013b; Veldkamp et al., 2012).

Insects are well highlighted as an alternative protein source for animal feed. When related to environmental sustainability, the use of insects as a decomposer of decaying organic waste can be employed easily because it requires low/simply-tech, then at the end of the treatment process could produce larval biomass as a substitution for protein sources (such as a fish meal), especially in aquaculture. Insect-derived proteins, i.e. BSF meal, are believed to substitute protein sources in formulation feed animals. The protein content of BSFL compares favorably with the protein sources currently used in animal feeds, such as fish and soybean meals. Moreover, the amino acid and fatty acid contents of BSFL make them an ideal substitution for fish and soybean meals in the pet industry, livestock, and aquaculture feeds (Nyakeri et al., 2016; Ravi et al., 2020).

On swine farming, the land required to manage swine manure using BSFL is less than that to manage traditionally, which is using composting system (Newton et al., 2005a). In addition to land use, water is also an important resource in livestock and crops production to produce protein sources. A study conducted by Miglietta et al., 2015, revealed that the insect water footprint, accounted mealworms of *Tenebrio molitor* and *Zophobas morio* as examples, is more efficient compared with beef, and chicken, and pig meat. The results study showed that based on nutritional value (L/g protein), mealworms are lower in terms of water footprints compared with those farmed animals (23 L/ g protein, 57 L/ g protein, 34 L/ g protein, and 112 L/ g protein, respectively for mealworms, pork, chicken meat, and beef). Because mealworms are considered 100% edible. Although, that result will depend on the conversion efficiency of mealworms, from food into insect protein.

In the study conducted by Smetana et al., (2019), water depletion was considered as one of the main components during a life cycle analysis (LCA) for BSFL. The study included multiple diets including chicken feed, distillers' grain, wheat middlings, and fruit, and vegetable waste. The results found that chicken feed and Gainesville diet (a simple feed formulation used for fly production using similar ingredients to chicken feed but in different ratios) had the highest water depletion for all treatments for BSFL production at 0.39 L/ g and 0.33 L/ g, whereas the fruit and vegetable waste treatment had a negative water depletion of −0.072 L/g. These are all great improvements on the values above by Miglietta et al., 2015. The authors here highlighted the importance of feeding substrate on the water depletion and highlighted waste streams as being favorable in this regard. For those reasons, insects generally but more specifically BSFL that consume waste streams, are a suitable substitution to current protein sources for animal feed in terms of land and water use.

3. BSFL production systems

BSF is one of the most widely used decomposer agents to process organic waste (Diener et al., 2011a; Kim et al., 2021; Nguyen et al., 2015), because of its ease of handling and is relatively inexpensive to produce in a low-technology system. Therefore, the technical aspects of BSF processing must be designed appropriately so that the system becomes efficient and can be applied to all countries around the world.

3.1. Breeding system considerations

The BSF breeding system must consider the availability and consistency of organic wastes that might be a problem in certain geographical areas. Moreover, the designs system should be adaptable to the specific conditions of local communities and their socio-cultural conditions.

3.1.1. Availability of organic materials

Research revealed that in general, BSFL is a polyphagous insect on all types of organic materials of animals and plants (Bava et al., 2019; Nguyen et al., 2015). Diener et al (2011a) showed that BSF can be used to convert municipal waste with a reduction rate ranging from 65.5 to 78.9%. This study also noted the ability of BSF to remove hazardous materials, such as zinc, from waste streams, although it has been shown to have a negative effect on BSFL growth. Several other studies have shown the flexibility of BSFL to bio-convert organic waste, for example, Kinasih et al. (2018) on vegetable wastes, Pamintuan et al. (2019) on milkfish offal, and Parodi et al. (2020) on animal manure.

3.1.2. The effects of abiotic and biotic factors

Although BSF is reasonably easy to grow under various conditions, several studies have noted that abiotic factors, especially temperature and relative humidity, have a significant effect on BSF performance (Holmes et al., 2012, 2016; Tomberlin et al., 2009). Therefore, even though it is a small scale, the breeding system must still consider the influence of abiotic factors to obtain optimal results. Temperature is the most important abiotic factor and affects the development of larvae, prepupae, pupae, and the length of life of the adults. Chia et al. (2018a) noted that the most optimal population growth rate occurred at a temperature of around 30 °C, as well as for the parameter percentage survival of immature life stages.

Meanwhile, Holmes et al. (2016) showed a thermal tolerance limit, especially at low temperatures. The results of the study showed that eggs can still hatch at temperatures between 12 and 16 °C, while the lowest temperature that can still be accommodated by larvae is 19 °C. This fact is useful in breeding systems in countries that have extreme temperature differences. However, temperature intervention needs to be considered if optimal breeding or rearing is required. In another study, Holmes et al. (2012) showed the effect of relative humidity on the developmental performance of BSF. The results of the study showed that increased relative humidity would increase the success of hatching eggs and the emergence of flies, as well as shorten the development time. In addition to abiotic factors, a study by Barragan-Fonseca et al. (2018) showed that larval density per breeding container affected larval nutrient quality, especially on larval crude fat content parameters, although it did not affect larval protein content. The results of these studies indicate the potential of BSF to be developed in areas with diverse abiotic conditions, although in commercial breeding practice, optimal abiotic and biotic conditions must be considered.

3.1.3. Starting with local BSF

At the beginner level or small-scale breeding, trapping adult BSF from the wild is one of the easiest ways to build the colony. However, certain strategies are needed for BSF adults to come and lay eggs, for example, providing the most preferred organic wastes for laying eggs. For example, because livestock manure is abundant at the site, Ewusie et al. (2019) tested manure from pigs, chickens, and sheep as an attractant medium for collecting BSF eggs. The results showed that pig manure was the most preferred medium by BSF for laying eggs. Meanwhile, Sripontan et al. (2017) showed that fruit waste was the most preferred by BSF for laying eggs, compared to other types of waste, including livestock waste. These two studies show a preference for BSF on certain wastes, and the results vary between locations. Caruso et al. (2013) and Dortmans et al. (2021) explained that female BSF choose to lay eggs on media that can protect the eggs from predation as well as damage effects from abiotic factors, especially dehydration and sunlight.

3.2. Development of the breeding system

To adapt to community conditions and the purpose of breeding system, namely, to solve the waste problem and generate economic benefits, two breeding systems are being compared in this paper, namely the natural colonization system and the artificial mass breeding system (Čičková et al., 2015; Lohri et al., 2017). The first system is used in limited households or communities and is based on local needs and the availability of facilities. The second system, which is better managed, is used by a commercial company and is aimed at a wide-scale organic waste disposal program, as well as making business profits.

An example of a natural breeding system is developed by Nyakeri et al. (2017) in Kenya to provide an inexpensive source of protein for fish and poultry. The rearing system utilizes mashed maize grains, vegetable and fruit waste, fish, and manures found in the area. And the nutritional analysis showed that this system was able to produce larval biomass that could meet the nutritional needs of fish and poultry. Furthermore, Gougbedji et al. (2021) showed that a small-scale breeding system using movable plastic tanks was able to produce a feed of sufficient quality to optimally breed *Tilapia*. This is economically advantageous, especially if it is applied to lower-middle-income communities.

In contrast, artificial systems are designed to treat large amounts of organic waste and are designed using modern management systems and equipment to facilitate optimal and stable breeding conditions for BSF (Čičková et al., 2015; Lohri et al., 2017). They can be even based on sewage treatment (Joly and Nikiema, 2019), which may ensure the consistency of input feed This system is expected to produce prepupae biomass in high quantity and quality for business purposes and uniformity.

4. Various approaches to feeding BSFL

To obtain large larval and pupae biomass, BSFL can be produced using various types of feed, including organic waste (Wang and Shelomi, 2017), and/or formulated commodity feeds (Danieli et al., 2019). If one was to utilize commodities for BSFL feed commercially, it would result in the step of utilizing BSFL as a converter to be redundant, as commodity feeds can be fed straight to other animals without needing to be processed by BSFL. Naturally, BSFL is found to utilize organic matter outside of artificial production systems. According to Klammsteiner et al. (2021), the gut biome of the BSFL is genetically tailored for decaying organic matter and can be the account for higher antimicrobial peptides (AMPs) or survival rates on feeds that simulate or include organic matter. However, research to determine the optimal feed management/regimes need to be done so that the larval production system can become more efficient.

4.1. Feed characteristics for rearing BSFL

Feed quality determines the growth of BSF, both in the larval and adult stages (Nguyen et al., 2013). The feed ingredients used greatly determine the nutritional quality of the BSF body (Meneguz et al., 2018). The pre-treatment activities of the substrate are the key to produce BSFL. Mechanical crushing and heat treatment will improve the structure of the food waste so that the BSFL digestion (Pastor et al., 2015). The moisture content of the diet influences the growth of BSFL, and saturated conditions will decrease the decomposition rate (Cheng et al., 2017). The salinity of the substrate effect to BSFL growth rate when the food waste contains more salt larvae grow slowly (Cho et al., 2020). Barragan-Fonseca et al. (2019) conducted a study investigating the effect of semi-artificial diets on BSFL growth result showed larvae protein content was much less variable than fat content. They tested nine combination treatments of three carbohydrates and three protein concentrations. All combination diets support the complete growth of BSFL. In conclusion, a diet with high nutrient content and a low P: C ratio increased BSFL reproduction.

Bonelli et al. (2020) used in their experiment two specific substrates, with different nutrient compositions in rearing the BSFL: (i) Standard Diet for dipteran larvae (50% wheat bran, 30% cornmeal, and 20% alfalfa meal); (ii) Vegetable Mix Diet (fruits and vegetables). The BSFL can grow in organic substrates materials with low or high content of nutrients, suggesting that they can adjust in ingestion processes to achieve their nutritional requirements. The present work by Bonelli et al. (2020) proves that microbiota in the midgut of BSFL can digest various substrates with a different nutrient content that improves the ability to grow on multi diet materials. Research yield of rearing BSFL in poor diet, modifications of the digestive enzymatic process observed: (i) an increase in proteolytic activity, and (ii) a decrease in amylase and lipase activity. According to Klammsteiner et al. (2021), the food waste from the canteen is a suitable feed for BSFL, in some cases more favorable than the control chicken feed. Clifford and Woodring (1990) also reported a success story of rearing BSFL on 12 diet types with the high nutrient content composed from breweries by-products, which they demonstrated to be optimal for maximum production.

Tomberlin et al. (2002b) reported that three diets examined were suitable for rearing BSF. Table 3 showed various substrates used for BSFL rearing. The average value of nutrient content: protein 16.76%, fat 7.38%, ratio protein/fat 5.69, and mineral 4.73. Protein content maximum in the legume is 43.07%, fat maximum in poultry slaughterhouse waste is 42.90%, and mineral maximum in chicken feed diet is 19.61%. There are variances in research papers between natural and experimental rearing BSFL needs further standard operating procedures to refine and improve larval rearing for the mass production of these larvae and pupa.

4.2. Preferred growing environment by BSFL

Parodi et al. (2020) developed the preferred test method shown in Table 4. Results clearly show that BSFL prefers to live in pig manure rather than a mass-rearing diet, however mixing different diets diminished the preferences. The bioconversion of substrate into insect biomass varies greatly depending on the material given to the BSFL. Feed conversion rate (FCR) value ranges from very efficient as low as 1.11 with cookie meal (Nyakeri, 2018) until inefficient as high as 14.5 with municipal organic waste (Diener et al., 2011a) (see Table 5). The nutritional quality of diet affects the growth of BSF. Feeding with fruit and vegetable waste mixed has a low FCR, while animal manure and municipal waste have a high FCR. Meanwhile, the formulated diet has an FCR value in the range of 4.96–7.11 (Danieli et al., 2019).

4.3. BSFL gut microbiome

A study by Ao et al. (2021) investigated the potential metabolic and nutrient functions and taxonomic structure of the intestinal bacterial communities of BSFL where swine and chicken manure converted. They found Bacteroidetes, Firmicutes, Proteobacteria were dominant in the midgut of BSFL in those systems. Bacterial genes such as cellulases, proteases, and lipases can hydrolyze starch/cellulose, proteins, and lipids are encoding enzymes in the midgut of BSFL and thereby contribute to the digestion and recycling of biomass waste and other nutrients (Lee et al., 2014). Based on the study conducted by Yu et al. (2011) is proven that the addition of bacterial supplements is beneficial in BSFL culture. It is done by adding Bacteria (*Bacillus subtilis*) to chicken manure. The supplementation with *Arthrobacter* and *Rhodococcus* in the BSFL diet is promising too. Faster growing and harvestable larvae and

Table 3
Nutrient composition (on dry matter basis) of experimental diets used for the breeding of BSFL.

Larval diet	Protein (%)	Fat (%)	P/F	Mineral (%)	References
Individual diet					
Apple	3.82	0.44	8.80	0.32	Barbi et al. (2020)
Apple pomas	1.00	1.00	1.00	1.00	Heckmann and Gligorescu (2019)
Barley brewer's yeast	31.99	5.39	5.90	4.74	Chia et al. (2018b)
Barley brewer's yeast molasses	22.14	3.95	5.60	5.80	Chia et al. (2018b)
Barley water	30.33	6.38	4.80	4.15	Chia et al. (2018b)
Bio pulp	25.40	7.20	3.50	2.40	Gligorescu et al. (2020)
Canteen waste	32.20	34.90	0.90	7.00	Gold et al. (2020b)
Corn	24.04	3.01	8.00	0.97	Barbi et al. (2020)
Cow manure	11.10	4.40	2.50	19.30	Gold et al. (2020b)
Exotic fruit	3.84	0.43	9.00	0.48	Barbi et al. (2020)
Food waste	26.83	9.70	2.80	11.95	Klammsteiner et al. (2021)
Human faces	20.10	20.90	1.00	13.60	Gold et al. (2020b)
Kiwi	7.54	0.40	18.80	1.73	Barbi et al. (2020)
Legume	43.07	1.78	24.30	1.05	Barbi et al. (2020)
Malt	22.00	3.00	7.30	7.00	Heckmann and Gligorescu (2019)
Malt barley brewer's yeast	30.22	6.96	4.30	4.41	Chia et al. (2018b)
Malt barley brewer's yeast molasses	22.32	3.23	6.90	4.08	Chia et al. (2018b)
Malt barley water	28.89	6.78	4.30	3.80	Chia et al. (2018b)
Malt corn starch	27.38	6.46	4.20	3.03	Chia et al. (2018b)
Malt corn-starch brewer's yeast	27.72	6.04	4.60	5.14	Chia et al. (2018b)
Malt corn-starch brewer's yeast molasses	19.10	3.42	5.60	4.31	Chia et al. (2018b)
Melon	7.72	1.29	6.00	0.71	Barbi et al. (2020)
Mill by-products	14.50	3.00	4.80	6.20	Gold et al. (2020b)
Oil waste	3.58	39.10	0.10	2.47	Klammsteiner et al. (2021)
Peach	8.61	8.11	1.10	0.52	Barbi et al. (2020)
Pineapple	3.85	1.56	2.50	0.62	Barbi et al. (2020)
Pomace	4.08	7.60	0.50	1.08	Barbi et al. (2020)
Poultry slaughterhouse waste	37.30	42.90	0.90	6.00	Gold et al. (2020b)
Rapeseed cake	32.00	9.00	3.60	7.00	Heckmann and Gligorescu (2019)
Seaweed	1.00	0.00	NA	4.00	Heckmann and Gligorescu (2019)
Sorghum barley brewer's yeast	31.39	9.48	3.30	4.32	Chia et al. (2018b)
Sorghum barley molasses	21.69	5.18	4.20	4.71	Chia et al. (2018b)

(*continued on next page*)

Table 3 (*continued*)

Larval diet	Protein (%)	Fat (%)	P/F	Mineral (%)	References
Sorghum barley water	29.43	11.8	2.50	3.72	Chia et al. (2018b)
Spent grain	6.00	3.00	2.00	1.00	Heckmann and Gligorescu (2019)
Sugar beet tops	4.00	0.00	NA	3.00	Heckmann and Gligorescu (2019)
Tomato	14.86	1.82	8.20	0.82	Barbi et al. (2020)
Vegetable canteen waste	12.10	28.90	0.40	7.60	Gold et al. (2020b)
Vegetable mix	10.30	0.70	14.70	4.60	Bonelli et al. (2020)
Wheat	11.00	2.00	5.50	1.00	Heckmann and Gligorescu (2019)
Mixture diet					
Basal diet (corn, soybean mix)	20.40	NA	NA	NA	Kim et al. (2020)
Ground barley, wheat bran, alfalfa mix	11.10	NA	NA	2.40	Danieli et al. (2019)
Ground barley, wheat middlings, alfalfa mix	13.80	NA	NA	4.10	Danieli et al. (2019)
Ground barley, wheat middlings, alfalfa, wheat straw mix	11.20	NA	NA	4.10	Danieli et al. (2019)
Ground corn, wheat bran, alfalfa mix	10.60	NA	NA	3.30	Danieli et al. (2019)
Formulated artificial diet					
Artificial diets P7NFC78	7.00	0.60	11.70	3.30	Gold et al. (2020b)
Artificial diets P13NFC8	12.60	0.60	21.00	3.30	Gold et al. (2020b)
BSFL0 diet	18.49	NA	NA	5.11	Mbhele et al. (2019)
BSFL25 diet	18.52	NA	NA	5.01	Mbhele et al. (2019)
BSFL50 diet	18.81	NA	NA	4.92	Mbhele et al. (2019)
BSFL75 diet	19.32	NA	NA	4.95	Mbhele et al. (2019)
BSFL100 diet	19.23	NA	NA	4.89	Mbhele et al. (2019)
Chicken feed-1	21.00	4.10	5.10	6.00	Gligorescu et al. (2020)
Chicken feed –2	35.99	4.10	8.80	19.61	Klammsteiner et al. (2021)
CSMA	19.00	3.00	6.30	8.00	Tomberlin et al. (2002b)
Danish cookies	6.00	21.00	0.30	0.00	Heckmann and Gligorescu (2019)
Gainesville diet	15.30	3.80	4.00	6.30	Tomberlin et al. (2002b)
Layer hen ration	15.00	3.00	5.00	13.70	Tomberlin et al. (2002b)
Standard diet	14.10	2.70	5.20	5.10	Bonelli et al. (2020)
Average	**17.62**	**7.38**	**5.69**	**4.73**	

Note: NA = not available, P/F = protein/fat ratio.

pupa save industrial BSF production costs and increase benefit (Kooienga et al., 2020).

Table 4
The number of larvae (%) that preferred the mass-rearing diet and pig manure.

Reared on	Manure	Mass-rearing diet	No choice
Any	97.80	1.60	0.60
Manure	85.15	12.45	2.40
Mass-rearing diet	87.15	12.5	0.35

Source: Parodi et al. (2020).

Table 5
The Feed conversion ratio (FCR) value of rearing black soldier fly on various substrate.

No	Substrate	FCR	Reference
1	Avocado	3.05	Nyakeri (2018)
2	Banana	1.97	Nyakeri (2018)
3	Banana peelings	4.50	Nyakeri (2018)
4	Brewer‘s waste	2.70	Nyakeri (2018)
5	Chicken manure	13.40	Sheppard et al. (1994)
6	Cookie meal	1.11	Nyakeri (2018)
7	Faecal sludge	3.40	Nyakeri (2018)
8	Feed mixed	2.40–3.60	Heckmann and Gligorescu (2019)
9	Food remains	2.60	Nyakeri (2018)
10	Food waste	1.70–3.60	Gligorescu et al. (2020)
11	Formulated diet	4.96–7.11	Danieli et al. (2019)
12	Human feces	2.00–3.00	Banks et al. (2014)
13	Kales	3.83	Nyakeri (2018)
14	Municipal organic waste	14.50	Diener et al. (2011a)
15	Pig manure	9.60	Newton et al. (2005b)
16	Pineapple	2.45	Nyakeri (2018)
17	Water melon	2.04	Nyakeri (2018)
	Average	**4.67**	

Note: FCR = Total feed consumed/Total weight of product produced. Where Total weight of product produced = final weight of the product – the initial weight of the product.

The ability of BSF to produce antibacterial peptides against *Helicobacter pylori* adds to the potential of BSF to further investigate concerning bioprospection (Alvarez et al., 2019). Mahlapuu et al. (2016) showed that most antimicrobial peptides (AMP) kill microbial pathogens directly but others by modulating the host defense systems. Antimicrobial peptides are also known as host defense peptides, are short-chain positively charged peptides. Vogel et al. (2018) had a study on the relationship between feed and immunity reported that 50 genes were encoding antimicrobial peptides. In summary, the BSFL can live in a variety of natural or artificial feed or organic waste. The growth of BSFL in fruit and vegetable waste is better than artificial feed or animal manure. A standard protocol in measuring the parameters of BSFL growth and conversion of organic waste has to be reconstructed.

4.4. *BSF genetic selection for organic waste processing*

As the BSF genome encodes the highest AMP family in insects (50 AMPs) (Zhan et al., 2020), it is of interest whether the genetics of BSF can be altered through the introduction or withdrawal of particular types of substrates leading to genetic selection for specific diets. As BSF are so naturally well adapted to feed which requires high immune responses, it may be interesting to understand if cleaner or less bacterial loaded feeds reduce the ability of the BSF to express the anti-microbial response it naturally possesses. Replacing synthetic antibiotics and probiotics used in the feed industry such as in aquaculture and swine diets is one of the functional benefits of including BSFL products into the diets of other animals apart from the nutritional composition of the products. Lowering AMP expression in BSFL is not desired from this point of view. Eriksson and Picard (2021) state that optimizing for an economic trait could be at the expense of a fitness trait such a flight ability (the ability of a fly to take flight) or survivability (ability to survive). Therefore, attempting to optimize the BSF for artificial diets with raw materials in place of rotting organic matter as per their natural habitat, maybe at the detriment of other traits also required for economic and productive success in mass rearing. Therefore, using the natural ability of the BSF to express AMPs by playing toward their natural affinity for organic waste processing may also in turn be preserving associated positive traits required for optimal growth, breeding, and survival.

5. Waste management: BSF production is a competitive solution

To create an integrated waste management solution, the system should have economic value, be commercially accepted and applicable, as well as easy to maintain and sustain. Organic waste management using BSF manage to provide many of these benefits. With its relatively low cost in transport and maintenance value compared to compost (density related), BSFL production as a waste management solution is a promising alternative. Despite its benefits of organic waste processing, the production of BSFL has undoubtedly a high economic value with its commercial product as animal feed, biodiesel, and chitin.

5.1. BSFL as animal feed

Conversion of organic wastes using BSFL into larvae or prepupae with various benefits is a sustainable recycling technology (Diener et al., 2011b). Despite that the nutrition content in the body of BSFL is varies depending on the substrate and age, the high crude protein and high crude fat content of BSFL make them a good nutrition source of animal feed (Kim et al., 2019; Spranghers et al., 2017).

BSFL can be used as animal feed either in processed form (as dried larvae or extracted oil/protein meal) or as live larvae. Protein extracted from the larvae and pupae proved to be as good as soybean or meat meal in the common feed composition (Čičková et al., 2015). Protein in BSFL contains ten essential amino acids that are required to present on animal feed: arginine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine (Halver et al., 1957, Halver and Shanks, 1960; Shumo et al., 2019b). According to Muller et al. (2017), the quality of animal feed is determined by the amino acid composition of proteins. The content of amino acids in BSFL varies depends on the substrate. In a study by Shumo et al. (2019b), the highest total amino acid content on BSFL occurs on larvae that are feed with kitchen waste.

Data presented in Table 6 showed that only methionine was the only amino acid that did not meet the FAO recommendation and tryptophan was undetermined. Meanwhile, histidine content was three times higher and the rest were slightly higher than the recommended value. Essential amino acids content in BSFL is relatively higher than other sources of common protein used in animal feed (Table 6). Overall, the amino acid content in the BSF meal was higher than the soybean meal and soy concentrate. Furthermore, it is favorably with fish meal and soy protein as a protein ingredient.

5.2. BSFL lipids for biodiesel and cosmetics

Despite its beneficiary as animal feed, a large amount of nutrition content in BSFL lies in its fat content (particularly in the BSF prepupae) and is a valuable feedstock for the production of biodiesel. Li et al. (2011) reported that the fat is isolated from larvae using the modification of petroleum ether with acid-catalyzed esterification of free fatty acids (this aims to compress the acidity of crude fat) and alkaline-catalyzed transesterification. After extracting the fat from BSFL, the fat can be used as biodiesel. Compared to palm oil or sugar cane as present biodiesel sources, BSF requires a shorter period in production, provides better fertility, and has more land efficiency since it needs lesser space. The lipid quality produced by BSFL is determined by the quality of biodiesel (Gianetto et al., 2020). Compared with the European Biodiesel Standard (EN14214), BSFL fat-based biodiesel has a positive result in which each of the fuel properties meets such requirements (Table 7). The oil derived from BSFL has been investigated for potential use in skincare products (Verheyen et al., 2018), however, were found to be less suitable compared with locust or cricket oils due to the high levels of lauric acid (>60%) in their fatty acid profile. All of the insect oils tested (BSFL, locust, and cricket) were found to require odour, colour, phospholipid, and free fatty acid removal to increase their applicability in this market.

According to the previous study by Li et al. (2011) and Zheng et al. (2012), BSFL-biodiesel is favorable as high-quality biodiesel. Although

Table 7
Comparison of fuel properties of BSFL biodiesel with other biodiesel sources and European Biodiesel Standard.

Properties	EN14214	BSFL biodiesel	Rapeseed biodiesel	Waste cooking oil biodiesel
Density (kg/m^3)	860–900	860–895	880–911	877
Viscosity at 40 °C (mm^3/s)	3.5–5.0	4.9–6.0	4.4–5.8	5.23
Sulfur content (wt.%)	0.05	NA	<0.01	NA
Ester content (%)	>96.5	96.5–97.2	NA	NA
Water content (mg/kg)	<500	300	300	NA
Flash point (°C)	>120	123–128	NA	157
Cetane index	>51	53–58	45	48
Acid number (mg KOH/g)	<0.8	1.1	0.3	0.21
Methanol or ethanol (m/m)	0.2%	0.3%	NA	NA
Distillation (°C)	NA	360	352	NA
References	Canakci et al. (2008); Li et al. (2011); Zheng et al. (2012)			

NA = not available.

Table 6
Comparison of essential Amino acid content (mg/g) of Black Soldier Fly larvae (BSFL) with other protein sources and FAO recommendation.

Amino acid	BSF meal*	Fish meal	Soybean meal	Soy concentrate	Whey protein	2013 FAO recommendation
Arginine	62	63	26	46	21	NA
Histidine	48	20	10	16	22	16
Isoleucine	48	37	17	29	58	30
Leucine	77	65	27	49	102	61
Lysine	74	69	22	39	96	48
Methionine	6	26	5	8	19	23
Phenylalanine	62	33	18	33	33	41
Threonine	45	39	15	25	72	25
Tryptophan	NA	9	5	8	21	6.6
Valine	67	45	17	31	58	40
Reference	Muller et al. (2017)	Muller et al. (2017)	DiGiacomo and Leury (2019)	DiGiacomo and Leury (2019)	DiGiacomo and Leury (2019)	Wang et al. (2021)

Note: NA = not available.

* The protein content after dehydrating BSFL amounts up to 42%.

the acid number methanol or ethanol had slightly exceeded the requirement from EN14214 most of the properties meet the standard. Despite the fact that BSFL contains many of lipids, they are not commonly used for food production in many Asian countries and can be used as an alternative for sugar cane and corn in biodiesel production (Kim et al., 2021).

5.3. Chitin

Another valuable product gained from BSFL apart from its high protein and lipid content is chitin. Chitosan has a high economic value and is widely used as a chelating agent for products in medicine, cosmetics, and even biotechnology (Kumar, 2000; Nagdalian et al., 2018). Furthermore, chitin can be used to prepare chitosan by alkaline deacetylation (Muller et al., 2017). In the BSFL chitin can be found mainly in its cuticle, or exoskeleton, chitin is a structural component consisting mainly of acetyl glucosamine sugar moieties (Joly and Nikiema, 2019; Muller et al., 2017). The cuticle of insects consists of chitin in a matrix with cuticular protein, lipids, and other compounds. Due to its high percentage of nitrogen (6.90%) chitin is more appealing compared to synthetically substituted cellulose (1.25%) (Diener et al., 2011b). Although extracting chitin from BSF prepupae has not proved to be economically feasible. Due to the limited discussion in the following topic on the literature, it needs further investigation whether BSFL complements as a compatible source of chitin, compared to crab and shrimp shells, which are currently proved to be the main commercial sources of chitin (Diener et al., 2011b; Younes and Rinaudo, 2015).

5.4. Economic analysis

The relatively low cost of organic waste treatment and the revenue of high-value protein from larvae are the most economic benefits associated with the BSF technology (Diener et al., 2009; Spranghers et al., 2017). Due to the increasing demand for animal feed and the industry actively searches for alternative protein sources to complement or even substitute traditional feeds. So, BSF meal has high market opportunities. As a result, insects have become an interesting feed solution, including BSF, which is one of the most promising insect species for artificial rearing/farming and industrial feed production (Spranghers et al., 2017; van Huis, 2013a; van Huis et al., 2013b). In 2017 the international feed industry federation reported that the world feed production demand estimated to reach 1 billion tonnes, BSF meat has the potential to be worth 400 billion USD (Joly and Nikiema, 2019). Therefore, by the increase in conventional animal feed market prices the economic viability of BSF production is suggested to have enormous global market potential (Lalander et al., 2015; Makkar et al., 2014).

6. Conclusions

The bioconversion process using BSF in organic waste treatment has become a leading innovation due to their benefits such as their high production rate with low cost and shorter period of production. The natural habitat of the BSF in the wild is to utilize residual organic matter as a rearing substrate. This is one of the main reasons the species is chosen for mass production, due to the ability to consume multiple waste types to achieve excellent product performance in artificial environments. The rearing systems applied for BSF can be adjusted to the condition and demand required. Therefore, several production elements need to be considered when mass production is planned for a particular agricultural geographical area alongside any specific regulatory standards of a particular country. Namely, availability of organic waste, environmental biotic and abiotic factors, and a suitable system determined by socio-cultural conditions. The quality of the diet determines the growth of BSFL in the rearing process, as a feed with high nutrient content and a low P:C ratio increases BSFL production. The affinity for this type of feed can be seen in the ability to convert it to body mass during growth as well as other functional benefits being harnessed such as higher antimicrobial peptides (AMPs) and robustness for survival. In addition, the ability of BSFL to convert organic matter into useful end-products (like BSF meal, BSF biodiesel, chitin, etc.) while also requiring minimal transport and maintenance costs are the most economic benefits associated with the BSF technology. This review aims to highlight the importance of taking advantage of the high availability and low cost of waste streams as feedstocks for BSFL substrate, in place of raw materials such as wheat bran and maize/cornmeal. Converting low-value inputs that cannot be utilized directly for livestock and aquaculture diets into high-value feed ingredients like BSFL protein meal or BSFL oil which have application in many animal feed sectors allows these technologies to stand out from alternative waste management approaches.

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.

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