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Black Soldier Fly (*Hermetia illucens*) as a Potential Agent of Organic Waste Bioconversion

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ABSTRACT The use of black soldier fly (BSF) as a bioconversion agent has become an emerging breakthrough in waste processing. Organic wastes, such as household waste and livestock manure, can be used as a growth medium for BSF larvae and converted into favorable products. The average composting time of BSF larvae is around 12–15 days, which is faster than that of microbes or earthworms (4–5 weeks). BSF shows potential as a feed and food ingredient because it has a high nutritional content, such as enzyme, chitin, medium-chain fatty acid, and antimicrobial peptides, and can be used as a functional food ingredient. From an economical perspective, the short composting period and the role of BSF as a feed and food alternatives can benefit producers and consumers. The safety aspects of BSF utilization, including microbial safety, chemical safety, and environmental safety, warrant clarification to ensure BSF safety. However, some challenges arise regarding the use of BSF larvae (BSFL) as a bioconversion agent, such as for heavy metal residues, pesticide residues, pathogens, and antimicrobial gene transmission and residues that require the best composting strategy for mitigation. The environmental safety of organic waste treated with BSFL has a good impact; therefore, this strategy can be used to reduce global warming. Research must focus on effectively and safely enhancing the cultivation and processing of BSF and its applications as a functional food. In conclusion, BSF is a profitable alternative for organic waste bioconversion in developed and developing countries.

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1. INTRODUCTION

One of the huge challenges in almost all the cities in Indonesia is waste management. For example, the amount of waste in East Java in 2018 reached 5,064.88 tons/day consisting of 43.24% food waste, 17.73% wood branches and leaves, and 39.03% inorganic waste (Ministry of Environment and Forestry 2022). With the fast urbanization and agricultural land transformation into accommodation generating bulk waste in a quick span in some areas and the growing population, an upsurge in waste has become issue in developed and developing countries and may shortly become the most prominent concern for the world (Shazia Iqbal et al. 2021). The food supply chain generates 1.3 billion tons of agricultural and food waste every year (Yeona 2022). Current environmental, health, economic, and food security issues are related to the increasing use of unsustainable food and feed production, resulting in large amounts of organic waste. Thus, an economical and environmentally friendly strategy to manage organic waste is necessary.

The cultivation of insects as a bioconversion agent for organic wastes, such as food waste and livestock manure, can be adopted to produce nutrient-rich feed and organic fertilizer (Surendra and Kuehnle 2019). Insects can also act as an agent that bioconverts chicken and pig manure up to 50% and reduces phosphorus and nitrogen waste up to 75% (Newton et al. 2005a; Abd El-Hack et al. 2020). Several

types of insects belonging to the order of *Lepidoptera*, *Hymenoptera*, *Coleoptera*, *Hemiptera*, *Trichoptera*, *Odonata*, and *Diptera* can decompose organic wastes and reduce odors and the presence of pathogenic microbes (Surendra et al. 2020). Other insects can live in various organic wastes, such as the Hong Kong caterpillar or mealworm (*Tenebrio molitor*) (Azizah et al. 2019; Schiavone et al. 2019), locust insects (*Locusta migratoria* and *Schistocerca gregaria*) (Alegebeleye et al. 2012; van Huis 2013), crickets (*Acheta domestica* and *Gryllobates sigillatus*) (Wang et al. 2005; Navarro del Hierro et al. 2020), house fly (*Musca domestica*) (Adesina et al. 2012; Okah and Onwujiariri 2012), and black soldier fly (BSF) (*Hermetia illucens*) (Purnamasari et al. 2019).

The BSF is one popular insect potentially developed as a bioconversion agent for various organic wastes and livestock manure (*Hermetia illucens*). Its cultivation is easy, cheap, and fast, and this insect can simultaneously produce nutrient-rich animal feed (Liu et al. 2017; Stadlander et al. 2017), organic fertilizers (Liu et al. 2017; Song et al. 2021), fuel (Rehman et al. 2018; Kamarulzaman et al. 2019), and other derivative products (Caligiani et al. 2018). Several studies have mentioned the success of BSF larvae (BSFL) and pupae as feed for animals, such as fish (Bruni et al. 2018), poultry (Cullere et al. 2018), and pigs (Tan et al. 2020), as a substitute for the main protein source (usually fish meal or soybean meal). The BSF is not a vector of disease in humans

and animals (Diener et al. 2015) so it is safe for cultivation on a wide scale. Adult BSFs do not eat because their mouths do not function, and they die after laying eggs (Wardhana 2017). BSFL modify feces, reduce pathogenic bacteria such as *Escherichia coli* and *Salmonella enterica* (Erickson et al. 2004), and contain natural antibiotics (Newton et al. 2005b). These promising abilities must be explored to improve the production and productivity of BSF for the application of their derivative products to various types of livestock and plants. This review discussed the BSF life cycle, BSF bioconversion, utilization, safety aspects, and future application in producing various kinds of derivative products for organic fertilizers, nutrient-rich animal feed, bioactive compounds. The challenge of BSFL utilization was also addressed.

2. BSF LIFE CYCLE

The BSF is an insect that belongs to order Diptera and family Stratiomyidae and is found in subtropical and tropical climates (46° North –42° South Latitude) (Surendra et al. 2016). Its life cycle consists of five phases, namely, egg, BSFL, prepupa, pupa, and imago, (Martínez-Sánchez et al. 2011). BSF egg and larval development (Maglangit and Alosbanos 2021) are shown in Figure 1. The BSF life cycle is holometabolous and starts from the egg phase. BSF fly eggs are oval with a length of 1 mm and color of pale white that gradually turns yellow until hatching time; a colony usually produces 200–900 eggs (Fahmi 2015; Wardhana 2017). The number of eggs produced is directly proportional to the body and wing size of BSFs (Gobbi et al. 2013); adults can optimally lay eggs at a humidity of more than 60% (Tomberlin and Sheppard 2002). Female flies lay eggs near food sources, such as organic waste.

Eggs hatch into larvae within 3–6 days at 24°C (Diener et al. 2011; Holmes et al. 2012). BSFL have an oval, flattened body shape about 12–17 mm long and 11 body segments with several transverse hairs. BSFL obtain energy from various organic wastes that are still full of nutrition, such as excreta or chicken manure (Newton et al. 2005b), palm kernel meal/PKM (Fahmi 2015); tofu waste (Purnamasari et al. 2019); kitchen waste (Newton et al. 2005b); and fruit and vegetable waste (Žáková and Borkovcová 2013). The larva runs as a decomposer, and this stage is the longest phase in

BSF life cycle; BSFL are also known as a bioconversion agent. BSFL can live in wide temperature and pH ranges (Myers et al. 2008; Tomberlin et al. 2009), and their digestive tract contains several bacteria, such as *Micrococcus* sp., *Bacillus* sp., *Streptococcus* sp., and *Aerobacter aerogens* (Banjo et al. 2005). The quantity and quality of the media used in larval growth affect the body's nutrient content (van Huis 2013) and larval weight (Sundu and Dingle 2002). The growth rate of BSFL is extremely fast until the 8th day. The body-weight of the larvae also continues to increase until they are about to enter the prepupa stage. The white-skinned larval stage lasts for approximately 12 days. The larvae begin to turn brown and darken a week later (Rachmawati et al. 2015) and reach the prepupa stage for the next 25–31 days (Myers et al. 2008).

Prepupa does not require feeding and turns into a pupa by migrating to a dry and protected place. In the pupa stage, BSFL are at their maximum size and store a large amount of fat for defense during metamorphosis (Newton et al. 2005a). The prepupa phase starts on the 19th day, and the pupa stage begins on the 24th day. The pupa stage takes place for the next 8 days and lasts for 6–7 days until the individual becomes an imago/adult fly (Fahmi 2015; Rachmawati et al. 2015).

BSF adults only rely on body fat reserves obtained during the larval stage, so they do not act as a vector of disease and bacteria. Adult flies only need water to survive for 6–8 days (Tomberlin and Sheppard 2002) and require optimal environmental conditions for reproduction, namely, an average daytime temperature of 31.8°C; BSF adults are tolerant of various temperatures (range: 15°C–47°C) (Diener et al. 2011). The breeding and egg laying of BSF are influenced by time, light intensity (135 mol m⁻² s⁻¹) (Zhang et al. 2010), light wavelength (700 nm) (Briscoe and Chittka 2001), temperature (24°C–40°C) and relative humidity (30%–90%) (Tomberlin and Sheppard 2002).

3. ORGANIC WASTE BIOCONVERSION WITH BSF

Bioconversion by insects is an attractive solution that can overcome the problems of organic waste management. Bioconversion converts organic waste into high-value products, such as a source of methane energy, through fermen-

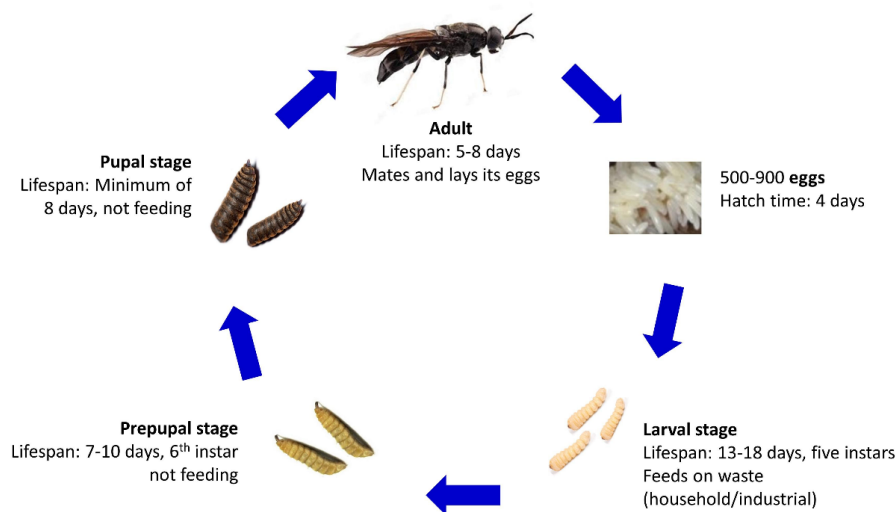


FIGURE 1. BSF egg and larval development (Maglangit and Alosbanos 2021)

TABLE 1. Organic waste reduction by BSFL.

Reducing material	Reducing the percentage of BSFL	References
Cattle waste	33%–58%	(Myers et al. 2008)
	12.7%	(Gold et al. 2020)
Poultry waste	50%–56%	(Myers et al. 2008; Siddiqui et al. 2022)
Organic waste	66%–79%	(Diener et al. 2011)
Fresh fruit waste	46.7%	(Lalander et al. 2019)
Vegetable waste	58.4%	(Gold et al. 2020)
Swine manure	86%–88%	(Awasthi et al. 2020)
Food manufacturing byproducts	52%	(Siddiqui et al. 2022)
Human feces	39.1%–48.6%	(Gold et al. 2020)

tation involving living microorganisms, such as bacteria, fungi, or insect larvae (family: *Chaliforidae*, *Mucidae*, and *Stratiomyidae*) (Newton et al. 2005a). Furthermore, insect larvae can convert a large number of nutrients from organic waste (Leong and Kutty 2020) by up to 70% in two weeks and store them as protein-rich biomass to replace fish meal (Diener et al. 2015). BSF life cycle and potential benefits are shown in Figure 2.

BSFs have been propagated as organic waste converter agents because they eat a variety of organic materials four times their body weight and produce larvae containing 40% crude protein and 30% fat biomass. Therefore, the conversion of organic waste by BSFL is an attractive recycling technology with many uses, such as in waste reduction and stabilization and value-added animal feed, and opens up new economic opportunities for small entrepreneurs in developing countries (Diener et al. 2015; Nguyen et al. 2015). Waste reduction by BSFL is commonly used as an indicator to determine the bioconversion efficiency of the type of waste and is calculated as the difference between the feed provided and residue and then divided by feed (Siddiqui et al. 2022). Larval survival and growth are affected by the C/N ratio, protein level, and volatile solid content of the provided substrate (Rehman et al. 2018; Gold et al. 2020). High fiber concentrations negatively affect the bioconversion efficiency and larval growth (Bohm et al. 2022). Other factors influencing bioconversion include feeding rate, larval density, and feeding frequency (Diener et al. 2011). The added synergistic microorganisms, fungi, or exogenous microbes improve the bioconversion of organic wastes and do not negatively affect the nutrient value of BSF biomass (Surendra et al. 2020). The percentage of reduction by organic waste bioconversion is shown in Table 1. By comparison, the percentage of reduction using vermicomposting is only 4%–5% of food waste (Ali et al. 2015) and 18% of cow manure (Contreras-Ramos et al. 2005). He et al. (2021) reported that bioconversion using the mealworm of rice straw and corn straw can produce carbon reduction of up to 16.3% and 13.67%. Therefore, BSFL bioconversion is the most efficient among these methods.

Residues from BSFL are used as compost and have nutritional levels suitable for use as fertilizers and soil amendments. The rate of waste consumption by BSFL varies according to the type of waste, number of larvae, moisture content, temperature, and larval size (Alvarez et al. 2019). BSFL can reduce pathogen bacteria, such as *Escherichia* sp., *Salmonella* sp., *Vibrio* sp., and *Yersinia* sp., allowing the

compost end product to meet the requirements for use as fertilizer and/or soil improver (Awasthi et al. 2020). Table 2 shows the emission potential of several greenhouse gases (GHGs) during composting by some bioconversion agents. BSFL produces less and cleaner GHG than vermicompost and traditional composting in agricultural waste and food waste substrate. GHG emission is also determined by other factors, such as C/N ratio, pH, composting time, substrate, and aeration rate (Rehman et al. 2018; Li et al. 2020; Lindberg et al. 2022a).

4. BSF NUTRIENT COMPOSITION

Among various insects that can be developed as feed, BSF has quite high protein and fat contents ranging 40%–50% and 29%–32%, respectively (Bosch et al. 2019). These nutrients include essential amino acids; thus, allowing BSF to be a substitute for fish meal and MBM for animal feed. BSF is also rich in lauric acid (36.74%) (Fitriana et al. 2022). BSFL can be produced easily and quickly (Mawaddah et al. 2018) and can decompose various kinds of organic matter, such as livestock manure, vegetable waste, and kitchen waste (Spranghers et al. 2018), and agroindustrial byproducts (Meneguz et al. 2018). The use of different substrates will produce different biochemical compositions of larvae. Protein sourced from insects is environmentally friendly, economical, and has an important role in nature. Insects have high feed conversion rates and can be reared and mass-produced (Li et al. 2015) and can reduce virus survival (Lalander et al. 2015). Antibacterial studies in Korea showed that methanol extract from BSFL has antibiotic properties against gram-negative bacteria but is not effective against gram-positive bacteria (Kim et al. 2011).

Omega-3 and -6 fatty acids are present in BSF biomass and could be enriched by manipulating the composition of substrates, such as microalgae, seaweed, and fish offal (Surendra et al. 2020). BSF accumulates manganese (Mn) and micronutrient calcium (Ca) up to 6% of dry matter (Spranghers et al. 2018). BSFL has relatively high protein content and can be potentially used as protein sources (Table 3). Compared with other insects usually used for animal feed, such as Jamaican field cricket and mealworm with crude protein levels of 67.7% and 64.5%, respectively, BSFL has lower crude protein level at 44.7%–44.9%. Despite this disadvantage, BSFL adults aged 2 weeks have the lowest methane emission compared with Jamaican field cricket, mealworm, and soybean during rumen fermentation (Jayanegara et al. 2017).

5. POTENTIAL USE OF BSF AS FEED

Feed availability is a major factor in the success of livestock business, whether in the form of poultry, ruminant, or fish farming. Fish waste is the main raw material for supporting protein, but its availability fluctuates. For increasing the sustainability of meat production, insects have emerged as innovative feed ingredients for several livestock species. The effect of BSFL on animal performance is shown in Table 4. Potential alternative raw materials with high protein content include maggots from BSF, which also contain animal protein. As a component of a complete diet, BSFL meal contains the recycled lost nutrients because the residual fatty acids and amino acids of organic wastes are incorporated into the biomass high in fat and protein (Henry et al. 2015) and even functional molecules (Iaconisi et al. 2017).

BSFL meal can be applied in livestock diets as a replacement part or even a complete substitute for conventional protein sources, such as soybean meal and fishmeal. However, insect meal has a high ratio of omega 6 and monounsaturated fat, and fish meal is rich in EPA (14%) and DHA (16%) (Barroso et al. 2017). Heavy metals and nonessential elements do not accumulate in BSFL but rather in the residues (Bohm et al. 2022).

6. BIOACTIVE COMPOUND IN BSF

Owing to its nutritional content, BSF is generally used as feedstuff of animals, including those in aquaculture and livestock production. The use of BSF as a prebiotic and antimicrobial agent has been discovered recently, and the bioactive components of BSF were found to be enzymes, chitin, peptides, and polysaccharides. The bioactive content is a component that has potential to be developed in addition to BSF as a protein-rich feed source. The protein of BSFL can be hydrolyzed to produce antioxidant peptides for functional foods (Zhu et al. 2020), cosmetic industries, and pharmaceutical products (Almeida et al. 2022).

6.1 Enzyme

The BSF also secretes beneficial enzymes related to digestion, such as amylase, lipase, and protease, during metabolism. The proteases with high activity in the digestive tract of BSFL include leucine arylamidase, α -galactosidase, α -mannosidase, α -fucosidase, and α -galactosidase (Kim et al. 2021). Cellulase is another enzyme that is presumed to be produced by BSFL, especially in its digestive tract, due to the discovery of the novel CS10 cellulase gene in BSF, which is expected to be an excellent opportunity for cellulase enzyme producers in the industry (Lee et al. 2014). Several studies also reported cellulase and ligninase enzyme activity, such as corncob fermentation with BSFL to reduce lignin by 2% and cow manure processing using BSFL to reduce hemicellulose level by 5% and cellulose content by 17% (Li et al. 2015; Gold et al. 2018).

6.2 Chitin

As a bioconversion agent, BSF has an excellent ability to produce chitin polymers or polymer of glucosamine up to 7% of BSF biomass on dry matter basis (Surendra et al. 2020). The chitin content of BSF varies with its life phase. Chitin content in various stages of BSF with different method analysis are shown in Table 5. In particular, the puparium and cocoon phases have the highest chitin content. Crystalline, the chitin form found in BSF, is alpha chitin. As a feed ingredient, the high chitin content of BSF can interfere with its digestibility as a monogastric feed. Nafisah et al. (2019) stated that physical activity, such as exoskeleton separation and fermentation using chitinolytic bacteria, can increase protein content and reduce fiber content by 65.02%.

The crystallinity index of chitin varies from 49.4% (BSFs) to 25.20% (BSF pupa). The chitins from BSF have good thermal stability with a maximum degradation of chitin BSF imago and BSF pupae at 363°C and 371°C, respectively (Purkayastha and Sarkar 2020). Soetemans et al. (2020) reported that the thermal property of chitin varies in different life stages with 366.1°C, 356.6°C, and 356.7°C for puparia, flakes, and adult BSF, respectively. Given the characteristics of chitin obtained from BSF, this insect has a huge opportunity to be developed for application in various

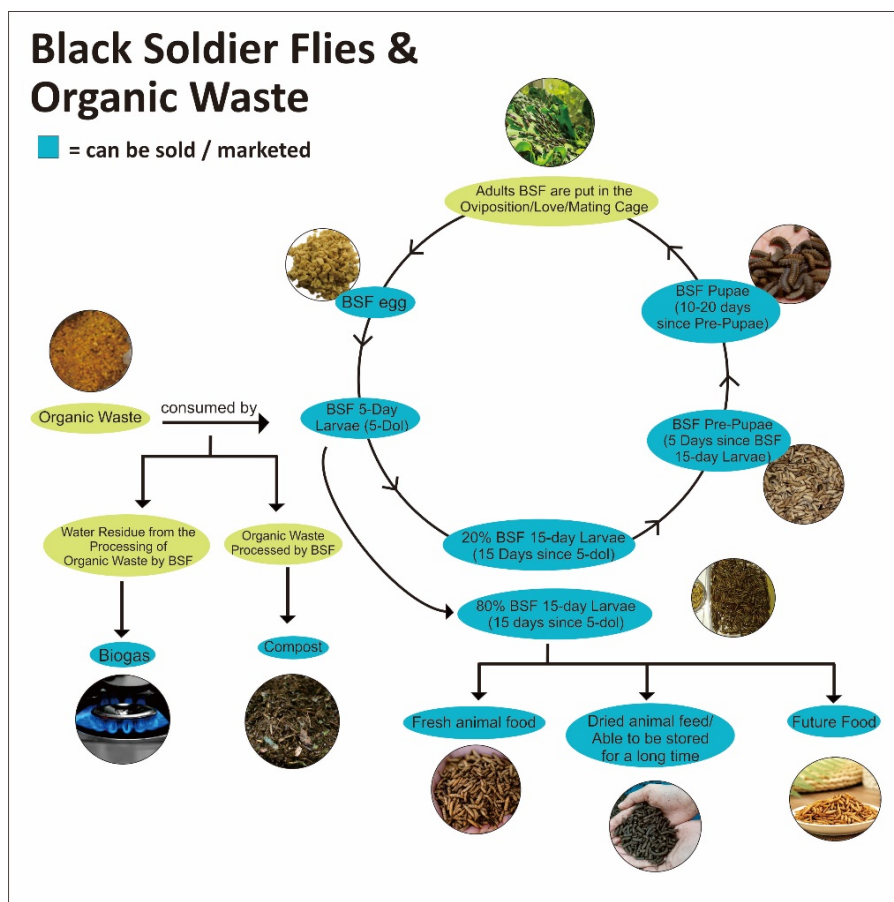


FIGURE 2. BSF life cycle and potential benefits.

TABLE 2. Green gases emission produces by different composting methods.

Variables	BSFL	Vermicomposting	Composting
Agriculture waste			
Total C loss (%)	-	53.2 (Yang et al. 2017)	48.9 (Yang et al. 2017)
Total N loss (%)	-	15.5 (Yang et al. 2017)	27.8 (Yang et al. 2017)
CH ₄ emission (g/kg)	0.08; 0.49; 0.76 (Pang et al. 2020)	2.28 (Yang et al. 2017)	10.52 (Yang et al. 2017)
N ₂ O emission (mg/kg)	1.03; 0.91; 1.36 (Pang et al. 2020)	5.76 (Yang et al. 2017)	12.29 (Yang et al. 2017)
NH ₃ emission	-	-	-
Total CHG emission (kg CO ₂ -eq/ton dm)	3.12; 16.93; 26.15 (Pang et al. 2020)	8.1 (Yang et al. 2017)	22.8 (Yang et al. 2017)
Food waste			
NH ₃ emission (g/kg)	0.15–1.68 g/kg (Pang et al. 2020) ; Below detection limit (Lindberg et al. 2022b)	4 ± 1 (Lleó et al. 2013); 15.3–34.0 Hwang et al. (2020)	2.61 (Komilis and Ham 2006) ; 2.37 (Yang et al. 2013)
CH ₄ (g/kg)	1.0–3.0 (Lindberg et al. 2022b) ; 0.06–0.79 (Lindberg et al. 2022a)	46.4–69.5 (Hwang et al. 2020)	88.1 (Hwang et al. 2020)
NO ₂ (g/kg)	0.19–1.0 (Lindberg et al. 2022b); 0.06–0.50 (Lindberg et al. 2022a)	0.27 (Hwang et al. 2020)	4.73 (Hwang et al. 2020)

- Not reported

TABLE 3. Nutrient content of BSF larvae fed with different substrates.

Substrate	Nutrient composition	References
Food waste	Crude Protein 32.80%–44.06%; Crude Fiber 30.42%–40.96%	(Fitriana et al. 2022)
Abattoir waste	Crude Protein 44%–44.4%	(Lalander et al. 2019)
Digested sludge	Crude Protein 42.3%–42.9%	(Lalander et al. 2019)
Pig manure	Crude protein 42.83% Crude lipid 36.52%	(Wang et al. 2020b)
Chicken manure	Crude protein 41.72% Crude lipid 36.18%	(Shumo et al. 2019)

industries, such as feed, food, textile industry, and tissue engineering, and as an adsorbent in water and wastewater treatment (Leni et al. 2017; Purkayastha and Sarkar 2020).

According to Leke-Aladekoba (2018), chitin from BSF has an antimicrobial activity against *Staphylococcus aureus*. Giving BSF meals to laying hens can also increase egg production and egg weight and adjust the composition of the gut microbiome, especially the chitin-degrading microbes that increase the production of short-chain fatty acids. Therefore, BSF feed can be used as an excellent prebiotic for the gut microbiota (Borrelli et al. 2017) and reduce the use of antibiotics.

6.3 Lauric Acid

Lauric acid is a medium-chain fatty acid (C12:00) or a saturated fatty acid that is popularly used as an antimicrobial agent, especially against gram-positive bacteria. One of the stages in the life cycle of BSF is prepupae, which are rich in protein and fatty acids; the fat in prepupae can reach as much as 0.58 g C12: 0/100 mL, which is beneficial to suppress the growth of *Lactobacilli* and *Streptococci* (Sprangers et al. 2018). The lauric acid content of BSF with various feeding strategies are shown in Table 6. These medium-chain fatty acids are widely used as antibacterial agents, such as a feed additive that can fight pathogenic bacteria including *Streptococcus suis*, *E. coli*, *Clostridium*

perfringens, *Salmonella poona*, and *S. aureus* and functions as an immunomodulator in livestock (Jackman et al. 2020; Widianingrum et al. 2019). Lauric acid also represses *Listeria monocytogenes*, which is a foodborne pathogen that can infect animal production (Çenesiz and Çiftci 2020), and can be converted into monolaurin that has antibacterial, antiviral, and antiprotozoal properties (Almeida et al. 2022).

The addition of lauric acid in the end also improves livestock productivity, such as feed efficiency, average daily gain, egg mass, and animal health in pig and poultry (Irawan et al. 2020; Elrod et al. 2019; Madeira et al. 2020). Lauric acid also improves productivity in beef and dairy cattle, including carcass percentage, IMF, and meat and milk quality (Nguyen et al. 2020; Wang et al. 2020a).

Lauric acid from BSF is safe for cattle and can be used to fight against the adult nymphs or larvae of *Rhipicephalus (Boophilus) microplus* (dos Santos et al. 2020). As an antiviral, it can also retrain African swine fever virus, herpes simplex virus type I, and coronavirus (Jackman et al. 2020; Aldridge 2020). Lauric acid can also be used as an anticoccidial (Price et al. 2013). Other essential fatty acid in BSF larva oil are palmitic, linoleic, and oleic acid often used as emulsifiers, emollients, and stabilizers of cosmetic formulation (Almeida et al. 2022).

6.4 Antimicrobial Peptides (AMPs)

AMPs perform an essential role in innate immunity as the first line of protection against pathogens, including bacteria, viruses, and fungi. AMPs are small molecules with size varying from 10 to 100 amino acid residuals and are produced by all living animals and plants (Vogel et al. 2018). Owing to their vast biodiversity, insects are among the most prosperous and most innovative origin for AMPs. Moretta et al. (2020) identified AMPs in BSFL using bioinformatics and found that 57 putatively active peptides have the potential to be developed as antimicrobials, antifungals, anticancer, and antivirals. Four peptides with an average size of 4.2 kDa can fight *Helicobacter pylori* (*Campylobacteria: Heliobacteria*) and *E. coli* (*Enterobacteria: Enterobacteriaceae*) and thus can be employed as a substitute for antibiotics against bacteria with increasing resis-

tance (Alvarez et al. 2019). Three AMPs from BSF, namely, hiddefensin-1, hidiptericin-1, and hiCG13551, were cloned and transferred to *E. coli* to produce transgenic antimicrobials to fight entomopathogenic bacteria in *Bombyx mori silkworm*; hiddefensin-1 and hidiptericin-1 successfully inhibited the growth of *E. coli* and *Streptococcus pneumonia*, and hiCG13551 suppressed the growth of *E. coli* and *Streptococcus pneumonia* (Xu et al. 2020). A study of AMPs in BSF confirmed that a new peptide (defensin-like peptide, DLP) could challenge gram-positive bacteria, including MSRA (Park et al. 2014). Another type of AMP is cecropin-like peptide 1, which can fight against gram-negative bacteria (Park and Yoe 2017). AMPs in BSFL are associated with more than 50 genes, 26 of which are classified as defensins. Therefore,

attention must be paid to gut microbiota adaptation in live-stock because the modification of feed given will modulate the gut microbiota population (Vogel et al. 2018). The antimicrobial peptides present in BSF biomass show potential use against fungi and viruses.

7. SAFETY ASPECT OF BSF UTILIZATION

7.1 Microbial safety

The popularity of BSF for organic waste bioconversion into quality products, including products with high protein content, and a source of polymers and beneficial bioactive materials, has continued to grow and is increasing globally. Therefore, the assessment of BSF safety as a portion of food,

TABLE 4. Nutrient content of BSF larvae fed with different substrates.

Animal	Treatment	Result	Reference
Broiler	substituting 250 g/kg (w/w) of the basal diet with BSFL meal	BSFL meals are excellent sources of AME for broilers and a valuable source of digestible amino acids	(De Marco et al. 2015)
Layer hen	replacement of soybean meal with BSFL meal on laying hens, from 24 to 45 week of age	led to a more favorable feed conversion ratio in hens	(Marono et al. 2017)
	A protein replacement of 25% with BSF larvae in the diet of laying hens	Positively affected on egg mass, Albumin to globulin ratio decreased, cholesterol and triglycerides decreased	(Abd El-Hack et al. 2020)
Quail	substitution of soya bean meal and oil with defatted black soldier fly larvae meal	feasible and provide the meat of comparable quality to that of quails fed a conventional diet	(Cullere et al. 2018)
	replacement to the common soya bean meal and soyabean oil with BSFL Meal up to 15%	Increase digestibility of nutrients, productive performance, carcass, and meat quality	(Cullere et al. 2016)
Duck	defatted BSF larva meal into the diets of Muscovy ducks	did not affect the slaughtering performance of the birds or the meat quality parameters	(Gariglio et al. 2021)
Swine	suitable ingredient in growing pig diets	its relative deficiency in methionine + cystine and threonine requires the inclusion of those amino acids for the preparation of balanced diets. The ash content of the meal is also high, and this requires attention	(Tan et al. 2020)
Fish	partially defatted black soldier fly larvae meal and mechanically extracted black soldier fly larvae oil (BSFLO)	The digestibility of diets containing BSFL meal or BSFL oil was significantly superior to in the Reference diet. The maximum inclusion of each BSFL meal and BSFL oil recommended in rainbow trout diets is 13% and 10%	(Dumas et al. 2018)
	suitable to replace up to 50% of dietary Fish Meal protein with Defatted BSFL Meal	boosted antioxidant status, decreased the hepatopancreas lipid and serum cholesterol content of juvenile Jian carp (<i>Cyprinus carpio var. Jian</i>)	(Li et al. 2017)
	partial replacement of Fish Meal protein up to 50% by Defatted BSFL Meal protein 50%–100% replacement of Soybean Oil with this n-3 enriched BSF Oil	reduced the feeding cost by 15.5% of European sea bass, <i>Dicentrarchus labrax</i> positively influences the performance and health status of juvenile mirror carp, improvement in the serum biochemical profile as immune status indicator, less inflammatory state of the liver and head kidney	(Abdel-Tawwab et al. 2020) (Xu et al. 2020)

TABLE 5. Chitin content in various stages of BSF with different method analysis.

Sources	Gravimetric (Soetemans et al. 2020)	Glucosamine (Soetemans et al. 2020)	Gravimetric (Wang et al. 2020a)	HCL-NaOH (Brigode et al. 2020)	ADF-ADL (Brigode et al. 2020)
Larvae	9.5%	7.8%	3.6		
Prepupa	9.1%	10.9	3.1		
Pupa	10.3%	10.7	14.1	25.39	21.19
Shedding	31.1%	23.7			
Cocoon	23.8%	22.4			
Flies	5.6	8.4	2.9	7.75	26.78
Flakes				20.69	7.94

feed, and pharmaceutical ingredient is essential considering that humans are end-users (Barroso et al. 2017; Lock et al. 2016). Safety assessment aims to prevent the spread and contamination of infection agents to humans. A study of BSF gut microbiota revealed that the use of BSF as feed requires the pretreatment of the feedstock and postharvest to prevent and depreciate pathogenic contamination (Khamis et al. 2020). BSF as a feed must be free from contamination or as a carrier that carries pathogens, pesticides, heavy metals, and pharmaceuticals (Surendra et al. 2020). BSF as a bioconversion tool converts organic waste into a protein source, so many concerns arise about its safety (Swinscoe et al. 2019). Livestock producers must maintain cleanliness and safety from farm to fork (FAO 2008).

Contamination can happen through the distribution of handling and storage of raw material of BSF. Microbiological contamination can also occur in the finished product during packaging and distribution or from the environment. Therefore, the identification and assessment of critical control points are necessary to ensure the safety of BSF naval vessels (Swinscoe et al. 2019). BSF production also affects its safety; for example, differences in BSF feed produce different macrobiotics in larvae. A food safety study provided feed that was inoculated with mycotoxins [aflatoxin B1, ochratoxin A or zearalenone, and deoxynivalenol (DON)] above the maximum limit (Reg (EC) 1881/2006; EC 2006) and found that these mycotoxins were secreted and did not accumulate in the body of BSFL (Varotto Boccazzi et al. 2017; Camenzuli et al. 2018). No evidence can confirm that BSF is a harbor from pathogenic viruses, but it may be a vector. As a protein source, BSF may also have the potential as an allergen. In some cases, the larva can even have viable Salmonella at the end of the rearing (Erickson et al. 2004). A recent study reported that BSFL did not show any significant reduction in Salmonella in the contaminated substrate during rearing (De Smet et al. 2021). By contrast, the substrate inoculated with *S. aureus* showed a decrease after 6 days and was counted below limit detection (Gorrens et al. 2022). Regardless, some investigations reported that extracts of BSFL have antimicrobial effects (Park et al. 2014; Xia et al. 2021). Being free of contamination is beneficial to maintain the utilization's safety aspect of a substrate.

7.2 Chemical safety

When BSF is used as a bioconversion agent, heavy metal contamination is possible if the organic waste used as BSF feed is contaminated with heavy metals. Diener et al. (2015) fed BSFL with a diet containing heavy metals Pb, Cd, and Zn at low, medium, and high levels and later detected these

heavy metals in the bodies of the larvae, prepupa, and adults. However, heavy metal zinc was not detected in the BSF larvae, prepupa, and adults when its contamination was at low levels. BSF can also accumulate naturally heavy metals (cadmium, lead, mercury, and arsenic) in feed ingredients, such as in seaweed with the highest retention percentage of 93% for Cd and the lowest of 22% for arsenic (Biancarosa et al. 2018). The accumulation of cadmium in BSF prepupa must be considered as an animal feed ingredient Diener et al. (2015). Exposure to heavy metal Cu and Cd also influences the fresh body weight of BSFL; exposure to Cu at 100–400 mg/kg did not influence the fresh weight of BSFL, exposure to Cu at 800 mg/kg significantly decreased the fresh body weight, and exposure to Cd at 100–800 mg/kg did not influence the fresh body weight (Wu et al. 2020). Heavy metal concentrations in BSF vary in each life stage. The larval stages has 7–170.5 µg/g Cd and 3.8–141.7 µg/g Pb, and the prepupa has 7.9–142.9 µg/g Cd and 1.5–40.1 µg/g Pb (Diener et al. 2015).

The feed produce is also important in the application of BSF as animal feed. For organic waste, it must be free from heavy metal contamination. Even low Cd concentration in feed can leave residues above the EU threshold (2 mg/kg Cd); low levels of Pb contamination are still below the threshold for Pb for feed (10 mg/kg Pb) (Diener et al. 2015). BSFL can also tolerate feed containing 6% plastic fragments or cardboard packaging without directly affecting their growth. The Bioaccumulation factor (BAF) of this contamination was identified, and the highest BAF was obtained from mixed cardboard packaging produced by vegetarian products (van der Fels-Klerx et al. 2020). BSFL bioconversion can create high-value biomass with low heavy metal concentrations and can reduce waste volume of up to 40% in 20 days (Bohm et al. 2022).

7.3 Environmental impact

Utilizing insects as feed can influence food stock, and a slight environmental but precise inspection of the resource is needed to examine the environmental safety, impact, and economics (Bosch et al. 2019). The use of BSF as a bioconversion agent is beneficial from an environmental aspect because it can convert various kinds of waste, including lime waste, vegetables, fruit, livestock manure, household waste, agricultural waste, and other organic wastes, into components of economic value, such as proteins, lipids, peptides, amino acids, and chitin. This method can be an alternative waste treatment that can have a positive impact on the environment and ecology (Liu et al. 2019a). BSF also suppresses the multiplication of houseflies, which often harm the environment and humans by causing pollution and carrying diseases (Bradley and Sheppard 1984). The application of BSFL as a bioconversion agent is a profitable alternative for developing countries that still face challenges in processing abundant organic waste (Mertenat et al. 2019). BSF can also help prevent global warming. Composting using BSF has 47 times lower CO₂ emissions than open windrow composting, which is accompanied by almost twice the risk of global warming compared with using BSF per 1 ton of biowaste (wet weight).

The use of BSFL as a substitute for fish meal tubs can reduce global warming potential by up to 30% (Mertenat et al. 2019). Its requirement for electricity source is only half of the composting. The BSF can reduce the accumulation of volatile fatty acids by 25.58%–80.08% and can in-

TABLE 6. The lauric acid content of BSF with various feeding strategies.

	Lauric acid content (%)	Reference
Chicken feed	0.05 ± 0.01	(Schreven et al. 2021)
Crambe press cake	0.20 ± 0.04	(Schreven et al. 2021)
Crambe seed meal	2.92 ± 0.07	(Schreven et al. 2021)
Flax cake	0.76 ± 0.18	(Hoc et al. 2020)
Food waste	36.96	(Mohamad et al. 2020)
Bacterial dried cell	48.70	(Mohamad et al. 2020)
Preconsumer waste	27.8	(Hong T. et al. 2018)

crease the final composting yield by increasing phosphorus as much as 42.30%–64.16%, total nitrogen (Kjeldahl analysis) by 45.41%–88.17%, and total nutrients by 26.51%–33.34%. BSF can also produce sugar products derived from BSFL grease and convert dairy manure into biodiesel. A total of 1248.6 grams of fresh manure was converted to 273.4 grams dry manure and produced 1200 BSFL for 21 days; 70.8 grams of dry BSFL was processed with petroleum ether to produce 15.8 grams of biodiesel and 86.2 grams of sugar (Li et al. 2011). With the above potentials, the BSF can be an alternative that is safe for the environment and can mitigate global warming.

8. ECONOMICAL ASPECT OF BIOCONVERSION ORGANIC WASTE USING BSFL

The feed accounts for the largest cost in livestock production; a main example is protein feed, which is often obtained from soybean meal and fish meal. For example, the feed cost is 85.31% of the total cost in the dairy business, 77.41%–80.97% for broiler chickens, and 74.42% for layer chickens (Haloho et al. 2013; Suwarta et al. 2012). This nutritional source can be obtained by substituting various local products and feed ingredients; however, the need for protein sources for livestock has not been satisfied (Frempong et al. 2019). The substitution of soy-based feed with BSF meal has a remarkably effect on the cost of feed. The price of feed per bird fed is lower with BSF meal (1 US \$ per bird) than with soybean meal (1.17 US \$ per bird) in the starter phase. Similarly, in the finisher phase, the cost is 1.63 US \$ for the BSF meal and 1.90 US \$ for the soybean meal. With low prices, the performance (body weight gain, FCR, average daily feed intake, and carcass weight) of broiler or cattle fed soybean meal and BSF meal does not significantly differ (Onsongo et al. 2018). From an economical perspective, BSF production varies greatly depending on the location, feed source, scale of production, and purpose of BSF production. It is also influenced by the production model factor using a tray or batch (Pleissner and Smetana 2020). Dry BSF production of 7.14 tons requires costs of 79,358.15 € and 5,281.56 € for equipment and daily operational costs. BSF production is deemed feasible if the dry BSF product is directly commercialized as a downstream product without further processing. However, processing through extraction and purification into certain chemicals, for example, the isolation of bioactive components (fatty acids, pigments, and chitin), can significantly increase revenue (Pleissner and Smetana 2020). BSF production costs include indirect cost, labor, consumables, and equipment that account for 13%, 45%, 12%, and 30% of the total cost, respectively (Zurbrügg et al. 2018).

Composting using BSF requires a shorter time (12–15 days) than composting using microbes or earthworms (4–5 weeks). The final product also varies from hummus to protein, biodiesel, sugar, and grease sugar. However, additional treatments are sometimes required to mature the final products from BSF composting (Madeira et al. 2020; Choudhury et al. 2018). Waste treatment using BSFL is a promising concept where a circular economy with maintained environmental and economic stability can be attained, especially among lower middle class economies (Zurbrügg et al. 2018). In Asia, various studies on the use of BSFL have been carried out to streamline its production and application in waste processing; BSF in biodiesel production, secretion of metabolites from BSFL, rearing tech-

niques, animal feed substitution have already been studied in China, Republic of Korea, Malaysia, Indonesia, Japan, and Vietnam (Kim et al. 2021). Studies on BSFL are still ongoing for the synthesis of economically valuable products and premium products that can be profitable. An economic opportunity is to organically produce BSFL products and their derivatives that are healthy, safe, and nutritious.

9. CHALLENGES AND POTENTIAL OF BSF IN THE FUTURE

The potential of BSFL as a source of protein for livestock and humans generates not only opportunities but also challenges because BSFL, which is an insect, is not recognizable or not yet accepted by all groups as a food ingredient and is considered taboo or unattractive. The safety of insect-origin food is still being studied. Some contemporary cultures have used insects as cuisines (Durst et al. 2010). The Food and Drug Administration in collaboration with the Association of American Feed Control Officials (AAFCO) through a Memorandum of Understanding imposed regulations in America regarding BSFL, specifically on how to produce, label, package, distribution, sell, import, and export it for food and feed. In August 2016, AAFCO agreed that dried BSFL could be cultivated as a feed and composting agent with a minimum fat content of 32% and 34% protein (Patterson et al. 2021).

As a bioconversion agent, BSFL is widely cultivated using organic wastes from agriculture and households. BSFL is allowed for use as animal feed, but its application in human food is being debated (Liu et al. 2019b; Gold et al. 2018). In the event of using BSFL as human food, postharvest processing must be conducted to ensure that it is free from contamination (Liu et al. 2019b). Several factors that influence insect decisions for food are feelings of disgust, household income and region, insect phobia, knowledge level, and social demographic factors, such as age and household size. Moreover, the perceived positive attributes associated with edible insects, the preferences of children in the household, and age and knowledge level have positive impacts on consumption frequency. Concerns of food safety and the insects' shape have negative impacts on consumption frequency. Some reports showed that insects can cause allergies of varying allergy levels, whether consumed directly or through processed food derived from insects. In China, consuming pupae silkworm caused acute allergies; in Botswana, someone was admitted to the hospital due to acute allergy from *Gonimbrasia belina* caterpillar (Okezie et al. 2010; Chung et al. 2001). The allergy is probably due to the identified tropomyosin in BSFL and crustaceans (Leni et al. 2020).

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Some studies indicated that the antibiotic resistance gene (ARG) has emerged due to aerobic manure composting (Zhang et al. 2016; Cao et al. 2020). BSFL composting approach can decrease the ARG by 95% in poultry manure after 12 days (Cai et al. 2018) and reduce lincomycin by 84.9% after 12 days of bioconversion (Luo et al. 2022). Another study also reported that BSFL decreased 97% of tetracycline after 12 days compared with the traditional method (Cai et al. 2018). However, another report stated that BSFL bioconversion does not have an influence in lowering ARG (Cifuentes et al. 2020). Niu et al. (2022) revealed that the density of BSFL during conversion influenced compost quality and was associated with ARG abundance. Elevated ARG level was found in gut of high-density BSFL during manure conversion and found to be best in the density of 100 larvae in 100-gram manure. These ARGs, including tetX and mcr-1, were reported from hosts, such as *Escherichia*, *Alcaligenes*, *Klebsiella*, and *Providencia* from fresh feces.

As food and feed and functional products, BSF and its derivatives can provide benefits to producers and consumers. In addition to financial benefits, the functional properties of BSF render it a healthy bioactive natural resource. Given that the environmental safety of organic waste treated with BSFL has a good environmental impact, this strategy can be one of the main efforts to mitigate global warming. Cheap protein sources are also beneficial for fish, beef cattle, dairy, and poultry farmers. In addition to the bioremediation of livestock manure (fecal sludge), BSFL can be used in entomoremediation for heavy metal wastes, such as Zn and Cd (Bulak et al. 2018). Research must focus on safely and effectively improving the processing and cultivation of BSF and its applications as a functional food. The development and enhancement of BSFL genetic quality must be carried out by identifying potential genes that regulate various traits for BSF production, such as manipulating protein as a source of food and functional food or fat material for biodiesel (Zhu et al. 2019).

10. CONCLUSIONS

BSFL is a popular insect and has potential as a bioconversion agent for reducing and recycling organic biomass. The potential of BSFL as a source of feed and food (edible product) has also been increasingly explored in food technology and animal feed, especially as a source of protein. Ease of maintenance and simple handling are important for products that are financially profitable and safe for the environment. BSF can be used to produce bioactive and prebiotic components, such as antimicrobial peptide, chitin, and enzymes, and even as a raw material for biodiesel. The safety of BSFL must be considered from the microbiological, chemical, and environmental aspects, including its low GHG emission during bioconversion. The study of production methods, utilization, and potential of BSFL warrants further and deep exploration to efficiently generate prod-

ucts that are truly profitable, environmentally friendly, and economical.

AUTHORS' CONTRIBUTIONS

L.P and H.K conceived the project and mainly performed the writing and literature review.

COMPETING INTERESTS

The authors declare no competing interests.

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