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Why for feed and not for human consumption? The black soldier fly larvae

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Abstract

With the surge in consumption of insects, the search continues to find ways to increase the popularity of insect-based products in the Western world. The black soldier fly larvae (BSFL), which is mainly utilized for animal feed, has great potential to provide a sustainable source of nutrients for human food. This review aims to discuss some of the key benefits and challenges of BSFL and their potential role as a food ingredient and/or product for human consumption. Few articles specifically discuss BSFL as a food source, therefore a comprehensive literature search strategy consisted of collecting and evaluating published data about BSFL as animal feed that could be relevant to its use in food. The hurdles that need to be overcome in order to introduce BSFL as a viable food option include safety concerns, technofunctional properties, nutritional aspects, consumer attitudes, and product applications for BSFL.

KEYWORDS

black soldier fly larvae, food safety, functionality, *Hermetia illucens*, insects as food, protein alternative

1 | INTRODUCTION

The search for novel, sustainable proteins to assist in mitigating the risks of climate change caused by traditional agriculture has led to increasing investigations into using insects as an alternative food source for human consumption (van Huis et al., 2013). Entomophagy is the long-time practice of eating insects, with a recorded 2,037 different insect species currently eaten globally in predominately non-Western countries (Jongema, 2015). Edible insects are a desirable food source due to their nutritional profile and their low environmental footprint. Many edible insects have high protein contents that are similar to that of animal protein, containing all of the essential amino acids required by humans (Bukkens & Paoletti, 2005; Chakravorty, Ghosh, Jung, & Meyer-Rochow, 2014). Insects contain a wide range of minerals, with especially high iron and zinc contents (Liland et al., 2017; Liu et al., 2017), which are deficiencies regularly found in both high- and low-income consumers across the world (Bukkens, 1997). Compared to traditional livestock, and some plant agriculture, edible insects have a low environmental footprint, as they have a high feed conversion efficiency (de Souza-Vilela, Andrew, & Ruhnke, 2019; van Huis, 2013), fast growth rate, and high fecundity (Mitsuhashi, 2010; Nakagaki & Defoliart, 1991) and some species, much like the black soldier fly larvae (BSFL), can recycle organic matter that would typically become waste (EFSA, 2015; Mertenat, Diener, & Zurbrügg, 2019; Woods, Hoffman, & Pieterse, 2019). This combination of high nutrient density and a low environmental footprint could potentially alleviate the pressures from some high-impact sectors such as the meat and dairy sector.

Although insects may have great potential for the future of food, the challenge going forward is consumer acceptance of insects (Hartmann & Siegrist, 2017; Tan et al., 2015; Verbeke, 2015). Food neophobia, a term used to describe consumers' reluctance to try or consume foreign or novel foods, plays a large role in Western consumers' willingness to accept insects as a food source (Verbeke, 2015). Insects are often met with disgust or apprehension among consumers and this remains one of the largest barriers for the commercialization of edible insects (Hartmann & Siegrist, 2017; Tan et al., 2015; Verbeke, 2015). The globalization of Western ideas has unfortunately also reduced the practice of entomophagy in developing countries where entomophagy was once a traditional food source (Chakravorty et al., 2014; Premalatha, Abbasi, Abbasi, & Abbasi, 2011). To reduce this barrier to entry, investigations have indicated that Western consumers are more willing to eat insects that are processed and disguised in a product, as opposed to eating them whole (Gmuer, Nuessli Guth, Hartmann, & Siegrist, 2016; Hartmann, Shi, Giusto, & Siegrist, 2015; Schösler, Boer, & Boersema, 2012). To increase acceptance, Western consumers are also more likely to consume insects in products that they are familiar with, as opposed to introducing insects to the market in completely new or unknown products (Tan et al., 2015). As examples, crickets (*Acheta domesticus* and *Gryllus bimaculatus*) and mealworms (*Tenebrio molitor*) have been successfully processed into burger patties at varied percentage inclusions (Caparros Megido et al., 2017; Schouteten et al., 2016), and are currently being sold in niche markets in Europe.

Some of the more commonly accepted insect species in Western markets are crickets (*Gryllidae*), grasshoppers (*Locusta migratoria*), mealworms (*Tenebrio molitor*), and silkworms (*Bombyx mori*) (EFSA, 2015). *Hermetia illucens*, or more commonly known as the black soldier fly larvae, have been somewhat overlooked as a viable option for human consumption. They have been thoroughly investigated as an environmentally friendly protein alternative for a wide range of livestock feeds (Mertenat et al., 2019; Woods et al., 2019) and to a lesser extent for pet food (Bosch, Zhang, Oonincx, & Hendriks, 2014). This review aims to evaluate the potential role of the BSFL as an alternative food source for human consumption. This review will consider existing research on BSFL as animal feed that can lend itself for human consumption as well as discuss some of the gaps in information that can put BSFL on the map alongside the currently accepted edible insect species.

2 | DATA SOURCES AND SEARCH METHODOLOGY

Research into BSFL for human food is still in its infancy, and to compile a review relevant for human consumption, a comprehensive review of the literature was conducted using four databases, namely, Science Direct, Scopus, Google Scholar, and EBSCO Host. A select range of keywords were used in the search to address the five major topics of this review and they are listed in Figure 1 along with the number of hits from each search. The search brought back a large number of peer-reviewed publications, most of which related exclusively to farming the BSFL and to its use in animal feed, and therefore, these articles were excluded from this review. Studies were evaluated by their title, keywords, and abstracts to determine their relevance and were only included if they contributed to the five themes (nutritional, food safety, technofunctional properties, consumer acceptance, and ways forward) of the review from a food perspective. To create a well-rounded review, keyword searches for literature regarding functionality, nutrition, and food safety risks of other more well researched edible insects ("mealworms" and "crickets") were conducted (Figure 1); however, due to the fact that there is far more research regarding their use as a human food, their inclusion in this review was restricted to ensure the focus remains on BSFL for human food. These papers were further evaluated to obtain a final 125 articles that have contributed to the content of this review.

3 | THE BLACK SOLDIER FLY

Black soldier fly (BSF; *Hermetia illucens* [L.] [Diptera: Stratiomyidae]), as a protein alternative, has demonstrated many advantages over numerous other farmed edible insect species (Barragan-Fonseca, Dicke, & van Loon, 2017; Wang & Shelomi, 2017) and as a result they are widely researched and farmed due to their ability to convert a wide variety of "waste" streams into quality proteins, fats, and minerals while demonstrating their potential for scalable and efficient production in the animal feed sector (EFSA, 2015; Mertenat et al., 2019; Woods et al., 2019). BSFL are able to do this as they have a selection of enzymes in their gut that allow them to consume a wide range of substrates, and this ability is useful, as they can reduce agricultural waste streams by feeding on them and converting it into their nutrient dense body mass (de Souza-Vilela et al., 2019). BSFL have demonstrated the ability to feed on substrates ranging from formulated animal feed to "wastes" streams such as human feces, abattoir waste, animal waste, spent grains, and organic waste from crop agriculture (Banks, Gibson, & Cameron, 2014; Barragan-Fonseca et al., 2017; Lim et al., 2019; Tschirner & Simon, 2015; Woods et al., 2019). The female BSF deposits approximately 500 eggs into organic matter and within 4 days the eggs hatch, and over a period of approximately 14 days, the growing larvae rapidly consumes the organic matter that surrounds them (Diclaro & Kaufman, 2009). In these 14 days, the BSFL go through six instars of development, before finally pupating (Diclaro & Kaufman, 2009). When

	Keyword Search		Science Direct	Scopus	Google Scholar	EBSCO
General	"black soldier fly larvae"		171	201	2140	409
	"hermetia illucens"		401	588	6100	928
Nutritional	"black soldier fly larvae" "hermetia illucens"	+ "nutritional"	133	122	1210	30
		+ "proximate composition"	32	22	333	7
		+ "amino acid"	87	70	766	25
		+ "fatty acid"	110	104	734	61
		+ "chitin"	73	68	666	8
Safety	"black soldier fly larvae" "hermetia illucens"	+ "microbial"	84	82	931	28
		+ "heavy metals"	41	37	397	11
		+ "mycotoxin"	15	5	83	2
		+ "allergen"	17	1	59	0
		safety"	228		1230	62
		+ "cross-reactive allergen"	1	0	4	1
Legislation	"edible insect"	+ "legislation"	102	23	436	4
		+ "regulation"	22	41	776	6
Techno-functional	"black soldier fly larvae" "hermetia illucens"	+ "protein isolation"	1019	0	21	312
		+ "fat"/"lipid"	659	70	678	98
		+ "chitin"	366	68	657	15
		+ "functionality"	18	5	44	2
Consumer acceptance	"edible insect"	+ "consumer acceptance"	100	32	442	5
		+ "consumer"	295	284	1360	41
		+ "food neophobia"	64	42	210	4
Other edible insects	"edible insect"	+ "techno-functionality"	16	34	96	3
		+ "nutrition"	420	143	1790	122
		+ "food safety"	169	79	828	21

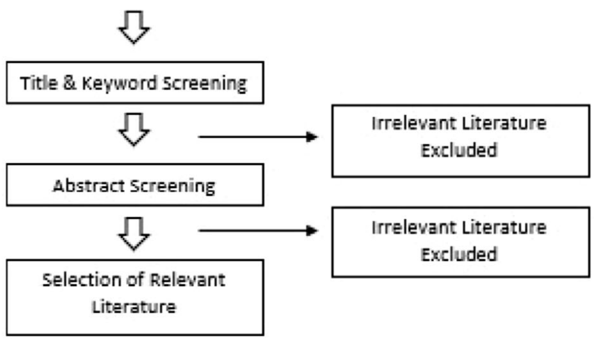

FIGURE 1 Schematic flow chart of process used to select literature, key searches, and number of hits per search

ready to pupate, BSFL crawl out of their feed, essentially harvesting themselves, allowing for less manual labor and ultimately a cost reduction in their farming (Wang & Shelomi, 2017). One of the added advantages of using BSFL as a waste converter is that the adult flies do not eat, thus reducing the risks of carrying and spreading disease, which is associated with some other decomposing insects such as the house fly (*Musca domestica*) (Sheppard, Tomberlin, Joyce, Kiser, & Sumner, 2002).

BSFL's ability to recycle waste is considered to be one of their biggest differentiating advantages over other insect species; however, it is also considered a major barrier and risk factor for human food (Fraqueza & Patarata, 2017; Wang & Shelomi, 2017). They are not a pest species, meaning there are less precautionary measures required to rear them (Barragan-Fonseca et al., 2017) and there have been studies demonstrating their innate ability to reduce harmful bacterial colonies and select viruses found in these waste streams (Lalander, Fidjeland, Diener, Eriksson, & Vinnerås, 2014; Liu, Tomberlin, Brady, Sanford, & Yu, 2008). This not only makes them a powerful waste reduction tool, but also suggests they may be less risky to use than some other edible insects, as they reduce some of the bacterial risk through their own biological pathways (Wang & Shelomi, 2017). Presently it is suggested to use a cleaner "waste" stream, such as spent grains and preconsumer vegetable matter (EFSA, 2015), for production of BSFL destined for human consumption for risk mitigation, as well as for standardization, although there is potential for introducing other "waste" streams into their diet depending on their ultimate food safety; however, more validation studies are required to fully understand the safety of farming BSFL destined for human consumption on waste streams.

With these advantages in mind, the potential environmental impact of using BSFL as a commercial food product could supersede the benefits of other accepted edible insect species. Although most farmed insects are considerably more sustainable and environmentally friendly than current livestock farming, the feed for the insects has been identified as one the main factors contributing to the sustainability of insect farming with "waste" streams being regarded as the best strategy for sustainable insect farming (Smetana, Palanisamy, Mathys, & Heinz, 2016). This falls neatly in the new agricultural concepts of circular economies and nutrient recycling, both of which have huge potential in shifting agriculture to far more sustainable systems.

4 | NUTRITIONAL ASPECTS

BSFL is an interesting insect from a nutritional perspective, as it has a diversity of micro- and macronutrients, and as a result it is widely used as a feed source for animals such as chickens (Pieterse, Erasmus, Uushona, & Hoffman, 2019), fish (Huyben, Vidaković, Werner Hallgren, & Langeland, 2019; Zarantoniello et al., 2020), and pigs (Veldkamp & Bosch, 2015). Their use as feedstuff for ruminants has been less successful due to the high chitin and fat content, which has a negative effect on fermentation and digestibility (Jayanegara, Novandri, Yantina, & Ridla, 2017). These nutrients found in BSFL are the same nutrients that are ideal for human health and can play an important role in a variety of sectors within the food industry ranging from meat alternatives (Bessa, Pieterse, Sigge, & Hoffman, 2019), to butter/margarine alternatives (Delicato, Schouteten, Dewettinck, Gellynck, & Tzompa-Sosa, 2020; Smetana, Leonhardt, Kauppi, Pajic, & Heinz, 2020), to bioactive compounds (Müller, Wolf, & Gutzeit, 2017), and potential functional ingredients (Caligiani et al., 2018).

4.1 | Macronutrients

BSFL are typically high in both protein and fat, with protein contents ranging from 30 to 53 g/100 g dry matter (DM), lipid contents ranging from 20 to 41 g/100 g (DM), and chitin, which predominately acts as a fiber in the human body (Bukkens, 1997), ranging from 2 to 9 g/100 g (DM) (Bosch et al., 2014; Bußler, Rumpold, Jander, Rawel, & Schlüter, 2016; Caligiani et al., 2018; Finke, 2013; Meneguz et al., 2018).

The nutritional composition of the BSFL varies and is affected by environmental factors, as well as the age of the larvae when harvested and the substrate consumed (Caligiani et al., 2019; Gold, Tomberlin, Diener, Zurbrügg, & Mathys, 2018; Liland et al., 2017; Rachmawati, Buchori, Hidayat, Hem, & Fahmi, 2010; Wang & Shelomi, 2017). The nutritional composition changes during the short larval stage, with the protein content decreasing with age, whereas the fat content is seen to increase (Liu et al., 2017; Rachmawati, Buchori, Hidayat, Hem, & Fahmi, 2015). Rachmawati et al. (2010) documented the protein content in the larval stage decreasing from 61% (DM) at 5 days old to 44% at 15 days old and 42% at 20 days old, whereas the fat content increased from 13% (DM) at 5 days old to 19% and 23% at days 15 and 20, respectively. A recent study found that the chitin content of BSFL decreased from the larvae (3.6 g/100 g) to prepupae (3.1 g/100 g) stage, and peaked during the pupae stage (14.1 g/100 g) (Wang et al., 2020). This information is useful and can allow for harvesting the larvae at certain times in their growth phase to obtain the desired nutritional profiles for specific applications. However, harvesting prior to pupation would introduce a challenge in harvesting the larvae from the waste feed prior to their prepupae stage, when they naturally migrate out of their feed source on their own (Wang & Shelomi, 2017). Although studies have demonstrated the significant effect of the substrate on the nutritional content of the BSFL, these effects are not always linear and require more research (Liland et al., 2017; Liu et al., 2008; Meneguz et al., 2018).

In general, BSFL have a lower protein content, and higher fat and chitin contents than some of the more commonly recognized edible insects such as mealworms and crickets (Table 1). This makes them a good food ingredient for both protein and fat applications.

TABLE 1 Nutritional content of beef (ground, raw), chicken (ground, raw), black soldier fly larvae, mealworm, and cricket (g/100 g) (Dry Matter Basis)

Species	Crude protein	Total fat	Chitin	Reference
Beef	50.8 to 65.4	18.6 to 32.7	0.0	U.S. Department of Agriculture, Agricultural Research Service (2019)
Chicken	66.8 to 86.2	10.0 to 26.8	0.0	U.S. Department of Agriculture, Agricultural Research Service (2019)
Mealworm (*Tenebrio molitor*)	50.1 to 76.2	27.2 to 31.1	3.7 to 5.7	Ghaly and Alkoaik (2009); Yi et al. (2013)
Black soldier fly larvae (*Hermetia illucens*)	30.0 to 52.9	20.0 to 40.7	2.1 to 9.0	Bosch et al. (2014); Bußler et al. (2016); Caligiani et al. (2018); Finke, (2013); Meneguz et al. (2018)
Cricket (*Acheta domesticus*)	64.4 to 73.6	12.3 to 22.8	7.6 to 19.1	Barker et al. (1998); Osimani et al. (2018)

4.2 | Amino acid composition

The amino acid profile gives a good indication of the quality of a protein. The amino acid profile of BSFL corresponds well to the reference standards set out by the World Health Organisation (Joint WHO/FAO/UNU Expert Consultation, 2007) (Table 2), indicating that they would be a good protein alternative for human consumption. BSFL also compares favorably to conventional protein sources such as meat and chicken (Table 2), and as a result could potentially be a sustainable alternative to these more traditional protein options. Lysine is of particular interest in developing countries, as it is a limiting amino acid in many grains, which are cheap and form a part of the staple diet of many people worldwide (Joint WHO/FAO/UNU Expert Consultation, 2007). The daily lysine requirement (45 mg/g protein) can easily be met by substituting with BSFL protein into the diet (Liu et al., 2017). The amino acid content of the larvae is not as affected by external factors as some of the other nutritional components; however, studies have shown that the amino acid content does vary over the course of the BSFL's life span, with higher levels of essential amino acids occurring in younger larvae, usually between 4 and 6 days old (Liu et al., 2017). The amino acid content is also affected by processing parameters, such as the killing method. Killing by freezing activates enzymatic pathways that results in the loss of cysteine and lysine, whereas blanching is seen to have no negative effect on the amino acid profile. It is suggested that cysteine and lysine are involved in the enzymatic browning, which would explain the losses in the frozen larvae (Leni, Caligiani, & Sforza, 2019).

4.3 | Fatty acid composition

Across studies, BSFL is found to be high in saturated fatty acids. Lauric acid (C12:0) is by far the most abundant fatty acid present and is known for its antimicrobial activity against gram positive bacteria (Caligiani et al., 2019; Meneguz et al., 2018; Müller et al., 2017; Rabani, Cheatsazan, & Davani, 2019). Lauric acid is followed by high concentrations of oleic acid (C18:1n-9), palmitic acid (C16:0), and linoleic acid (C18:2n-6) (Caligiani et al., 2019). The fatty acid profile is the most affected by the feed of the larvae with studies showing that by changing the feed input, the fatty acid profile of the larvae can be manipulated (Barroso et al., 2017; Cullere et al., 2019; Ewald et al., 2020; Lim et al., 2019; Liu et al., 2019). The age of the larvae also has a large effect on the fatty acid profile, with an increase in saturated fatty acids, and decreasing levels of unsaturated fatty acids in older larvae (Liu et al., 2017). The killing method was also found to have a significant effect on the lipid composition of the larvae, with freezing increasing the release of free fatty acids due to the inactivation of lipase activity on unsaturated fatty acids. Once again blanching was found to have less effect on the fatty acid profile than freezing (Caligiani et al., 2019).

4.4 | Micronutrients

Micronutrients, such as minerals, are an important part of the human diet, with emphasis placed on iron and zinc due to the extent of iron and zinc deficiencies in both developed and developing countries (FAO & WHO, 2005; World Health Organization, 2001). BSFL are high in both iron and zinc, with iron values ranging from 2.1 to 3 mg/100 g and zinc values ranging from 6.8 to 15 mg/100 g (Finke, 2013; Liland et al., 2017). Lean meat, which is typically considered one of the richest sources of zinc and iron, contains iron contents ranging from 1.1 to 1.8 mg/100 g and zinc contents ranging from 4.2 to 4.6 mg/100 g (Williams, 2007), which are lower than that of BSFL. The calcium content of BSFL is also naturally very high with contents ranging from 840 to 934 mg/100 g (Finke, 2013; Liland et al., 2017), which is similar to that of milk; milk is typically considered to be an important dietary source of calcium, with calcium ranging from 119 to 2,900 mg/100 g (Liu et al., 2017; Pereira, 2014). BSFL could make an interesting iron and zinc supplement especially in malnourished communities (Liu et al., 2017).

TABLE 2 Essential amino acid content of black soldier fly larvae (BSFL), mealworm, cricket, beef, and chicken (mg/g protein) compared to daily requirement (mg/kg/day)

Species	Ile	Leu	Lys	Met + Cys	Phe + Tyr	Thr	Trp	Val	His	Reference
Adult daily requirement	30.0	59.0	45.0	22.0	38.0	23.0	6.0	39.0	15.0	Joint WHO/FAO/UNU Expert Consultation, (2007)
Beef	44.2 to 51.9	56.4 to 98.4	82.8 to 106.5	36.0 to 47.2	69.8 to 73.5	38.7 to 44.7	5 to 11.3	49.2 to 66.6	32.5 to 32.6	U.S. Department of Agriculture, Agricultural Research Service (2019)
Chicken	45.5 to 49.0	82.7 to 86.5	86.5 to 96.1	36.3 to 36.4	73.7 to 76.3	41.6 to 44.8	8.4 to 12.5	47.3 to 51.7	30.3 to 37.3	U.S. Department of Agriculture, Agricultural Research Service (2019)
BSFL (*Hermetia illucens*)	40.0 to 41.0	61.0 to 75.0	54.0 to 65.0	14.0 to 47.0	31.0 to 110.0	36.0 to 42.0	6.0	39.0 to 55.0	28.0 to 33.0	Bosch et al. (2014); Liland et al. (2017); Caligiani et al. (2018)
Mealworm (*Tenebrio molitor*)	29.0 to 35.5	34.0 to 73.0	29.0 to 54.0	11.8 to 26.0	52.2 to 100.0	18.0 to 39.0	12.0	24.3 to 61.0	15.2 to 29.0	Ravzanaadii, Kim, Choi, Hong, and Kim (2012); Yi et al. (2013)
Cricket (*Acheta domesticus*)	36.0 to 42.0	66.0 to 73.0	53.0 to 56.0	15 to 25.0	63 to 92.0	35.0 to 36.0	6.0 to 9.0	55.0 to 60.0	21.0 to 26.0	Nakagaki, Sunde, and DeFoliart (1987); Yi et al. (2013)

5 | FOOD SAFETY AND LEGISLATION

The perceived safety of consuming insects including BSFL is an important factor in gaining consumer acceptance; it is therefore imperative to further investigate and understand the safety of consuming BSFL before advocating its consumption (Rumpold & Schlüter, 2013; Schrögel & Wätjen, 2019; Van Huis et al., 2013). The food safety element of consuming BSFL is of concern due to their role in recycling organic matter. The easiest initial approach to mitigate this concern would be to utilize BSFL reared on a clean "waste," in controlled farming environments to reduce the potential associated risks such as heavy metal uptake and potential pathogenic microorganisms (Rumpold & Schlüter, 2013; Wang & Shelomi, 2017). Although BSFL have primarily been farmed for animal feed purposes, resulting in little knowledge regarding the food safety risks of consuming BSFL, there is a large body of information regarding the safety of using BSFL for animal consumption when reared on a wide range of waste substrates, most of which could also be relevant to using BSFL grown on waste for uses in human food (Gold et al., 2018; Lalander et al., 2014; Liu et al., 2008; Proc, Bulak, Wiącek, & Bieganowski, 2020; Wang & Shelomi, 2017; Wanjiku, 2018; Wynants et al., 2019), with postharvesting processes such as blanching as an effective safety tool/hurdle (Klunder, Wolkers-Rooijackers, Korpela, & Nout, 2012; Larouche et al., 2019).

5.1 | Microbial risks

BSFL are innately decomposers and can reduce many of the microbial colonies in their substrate. Studies using indicator organisms have shown the reduction in *Enterobacteriaceae* colonies and *Salmonella* spp. in fecal sludge (Lalander et al. 2014), cow manure (Erickson, Islam, Sheppard, Liao, & Doyle, 2004), and chicken manure (Liu et al., 2008). BSFL are able to reduce microbial loads by eating bacteria found in the substrates, killing bacterial colonies with the high pH conditions of their gut, enzymatic reactions, and competitive gut bacteria that create undesirable growth conditions for the bacteria (Gold et al., 2018).

Using other edible insects species as a benchmark, studies have found a variety of microorganisms associated with insect species, with factors such as farming environment, feed, and postharvesting processes having the largest impact on the microbial load (Banjo, Lawal, & Adeyemi, 2006; Klunder et al., 2012. Preprocessing treatments on the BSFL such as heating have demonstrated a reduction in the microbial load of edible insects, with blanching being the most effective heat treatment to ensure microbial safety (Klunder et al., 2012; Larouche et al., 2019). Storage conditions would also play a vital role in the safety of BSFL. Studies on fried beetles and crickets indicated a rapid increase in the bacterial count when stored at room temperature, and a slower growth in bacterial numbers when stored in refrigerated environments (0 to 4 °C) (Banjo et al., 2006; Klunder et al., 2012). Drying insects for an extended shelf life is considered to be the best preservation option, and has shown favorable results under both refrigerated and nonrefrigerated conditions (Klunder et al., 2012). Globally, there are no stringent regulations regarding the microbiological safety of any edible insects; however, the Netherlands Food and Consumer Product Safety Authority has released a preliminary report indicating the high-risk microorganisms that are associated with edible insects and the limits of each microorganism regarded as safe to be consumed (NVWA, 2014). The microorganisms relevant to insects were based largely on the EU safety regulations for meat and seafood products (European Commission, 2005). This report does not specify microbial limits for specific insect species; therefore, it is suggested that further research goes into specifying the microbes and limits that relate specifically to BSFL as food. It is especially important to research the gut microbiome of BSFL reared on specific feed, under specific conditions as these factors can have a positive or negative effect on their microbiome (Wu, Wang, Xu, Cai, & Xie, 2020). This information is essential to fully understand the potential microbial risks to humans.

5.2 | Heavy metal and mycotoxin accumulation

A potential concern with using BSFL grown on “waste” streams is the accumulation of heavy metals in their biomass. BSFL have shown to accumulate heavy metals such as cadmium, mercury, copper, and lead, which are known to have adverse effects on human health when consumed in excess (Jaishankar, Tseten, Anbalagan, Mathew, & Beeregowda, 2014; Proc et al., 2020; Schrögel & Wätjen, 2019). Heavy metals such as copper and cadmium are found to have a negative impact on the gut microbiome of BSFL, which in turn could severely affect their ability to effectively reduce microorganisms in the feed. In fact, accumulation of copper and cadmium did enrich the growth of potentially pathogenic bacteria, which may find its way into the food if not effectively managed (Wu et al., 2020). The heavy metal content of the feed directly impacts the heavy metal content in the larvae (Diener et al., 2015; Proc et al., 2020) and therefore it is important to monitor the heavy metal content in the feed to mitigate the toxic risks to humans. To date, studies have indicated that BSFL do not accumulate mycotoxins, pharmaceuticals, or pesticides found in substrate due to their innate detoxification processes (Gold et al., 2018; Lalander et al., 2014; Purschke, Scheibelberger, Axmann, Adler, & Jäger, 2017).

5.3 | Allergen risks

The introduction of novel and cross-reactive allergens from BSFL to consumers is a safety concern that needs to be taken into account and fully investigated (Leni et al., 2020; Phillips & Burkholder, 1995; Srinroch, Srisomsap, Chokchaichamnankit, Punyarit, & Phiriyangkul, 2015). To date, there are reported cases of allergic responses when ingesting the common insect-based food colorant, carmine dye (E120 or Natural Red 4) obtained from Cochineal (*Dactylopius coccus* Costa) (Chung, Baker, Baldwin, & Chou, 2001). In China, where eating silkworm pupae is commonplace, there have been reported cases of allergic reactions to consuming the pupae with variations in the severity of the reactions (Ji, Zhan, Chen, & Liu, 2008). In Botswana, a patient was hospitalized as a result of an allergic reaction to eating the popular Mopane (*Gonimbrasia belina*) caterpillar (Okezie, Kgomotso, & Letswiti, 2010). In controlled skin sensitivity tests, protein extracts isolated from seven insect species indicated that 30% of previously allergic patients and 25% of nonallergic patients showed sensitivity to at least one insect extract (Bernton & Brown, 1967; Phillips & Burkholder, 1995). The patients in this study were not insect consumers, and the sensitivity of patients is assumed to be as a result of previous exposure to inhalation, physical contact with the insect allergens, or through accidental consumption (Bernton & Brown, 1967; Phillips & Burkholder, 1995).

Tropomyosin is the major pan allergen that has been identified in BSFL and crustaceans, indicating an increased likelihood of consumers that are allergic to tropomyosin in crustaceans would experience allergies when consuming BSFL (Leni, Soetemans, Caligiani, Sforza, & Bastiaens, 2020; Reese, Ayuso, & Lehrer, 1999). Tropomyosin has been identified as the cross-reactive allergen in mites and in shrimp (Reese et al., 1999). Another pan allergen prevalent in many insect species is arginine kinase. Arginine kinase, found in many varieties of prawn species, has been found in the lesser mealworm (*Alphitobius diaperinus*) (Leni et al., 2020b), field cricket (*Gryllus bimaculatus*), silkworm larvae (*Bombyx mori*) (Liu et al., 2011), the German cockroach (*Blattella germanica*) (Chuang, Su, Chiang, Lee, & Chow, 2010), and the Indian meal moth (*Plodia interpunctella*). In a shotgun proteomics study, arginine kinase was not identified as a major pan allergen in BSFL (Leni et al., 2020b); however, Broekman et al. (2017) identified the presence of arginine kinase in BSFL protein extract. Tropomyosin and arginine kinase are declared allergens for Arthropoda in the Allergen Nomenclature database (http://www.allergen.org/index.php) and have been found in both crustacean species and insect species. Patients who are allergic to prawns or shrimp have the risk of being allergic to BSFL, and should consume BSFL products with caution (Srinroch et al., 2015). Aside from cross-reactive allergens, there is also the risk of encountering novel allergens in BSFL. To date, a novel allergen, called Hexamerin1B precursor, was found in the field cricket (*Gryllus bimaculatus*). Hexamerin1B precursor is structurally similar to hemocyanin, which is a common allergen found in prawns and has the potential for cross-reactivity between these prawns and the field cricket (Srinroch et al., 2015).

Several studies have shown that some allergenic proteins are stable to heat processing or digestion, whereas others are readily inactivated (Besler, Steinhart, & Paschke, 2001; Kamath et al., 2014). In some cases, heat processing might also cause proteins to become more allergenic (Besler et al., 2001). Heating cockroach protein extracts does not eliminate allergic reactions and proteins still show positive reactions in the skin sensitivity tests (Bernton & Brown, 1967; Phillips & Burkholder, 1995). In the case of mealworms, heating reduced the allergic reactions (Van Broekhoven, Bastiaan-Net, De Jong, & Wichers, 2016). Hydrolysis has been used as a technique to reduce the allergic reaction to food proteins such as soy (Meinlschmidt et al., 2017) and in other insect species such as crickets (Hall, Johnson, & Liceaga, 2018). Hall and colleagues have demonstrated that hydrolyzing cricket proteins with alcalase reduced tropomyosin Immunoglobulin E (IgE) reactivity in shrimp allergic patients and that hydrolyzing the proteins even further to 60% to 85% degree of hydrolysis completely reduced the IgE reactivity to tropomyosin. Hydrolyzing BSFL proteins showed a reduction in immune reactivity, but there was partial preservation of IgE reactivity (Leni et al., 2020b), although with further research this could be a technique that could be used to reduce allergic reactions caused by BSFL proteins completely.

It is worth mentioning that although it is the insect proteins that are responsible for allergic reactions, prolonged exposure to chitin has caused sensitization in mice studies; however, its clinical effect in humans still requires further research and understanding (Burton & Zaccone, 2007).

5.4 | Legislative landscape

The legislative framework regarding insects as food is still in its infancy, and to date there are no specific regulations pertaining to the consumption of BSFL as human food (Wang & Shelomi, 2017). The European Union have recently clarified the position of edible insects in the new EU regulation (EU) 2015/2283 as a novel food (Regulation (EU) 2015/2283 of the European Parliament and of the Council, 2015). The EU regulation states that insects or their parts can be included in foods subject to their novel foods' authorization process. Each insect species and their intended use need to go through an application procedure prior to authorizing its use in human food. Currently, BSFL is not considered on the list of accepted edible insects in the novel foods regulation and would need to go through the application procedure prior to being sold in the European markets (Regulation (EU) 2015/2283 of the European Parliament and of the Council, 2015). The United States has taken a less proactive approach and has not set specific guidelines to regulate the edible insect market (Boyd, 2017). The Food and Drug Administration (FDA), which governs the safety of food in the United States, has not explicitly accepted insects as a food source; however, their standard response to enquiries is that insects are considered food if they are produced specifically to be used as food (Marone, 2016). The requirement is the same as all other food stuffs, and that is for the insects to be produced according to the current good manufacturing practices set out for human food (sec 201 (f)). The only additional requirement is for insect-based products to highlight the potential seafood allergies associated with eating insects. The FDA's failure to outline the regulations regarding insects as food makes it a gray area (Boyd, 2017), and it is suggested that in order to introduce BSFL as a food in the United States, BSFL grown and produced specifically for human consumption should adhere to strict food processing and safety guidelines. China, a country where insect consumption is commonplace, has no mention on consuming insects in their legislation, with the exception of silkworm pupae that was listed as an accepted food by the Chinese Ministry of Health (Liu, Li, & Gómez, 2020).

6 | TECHNOFUNCTIONAL PROPERTIES

In order to incorporate BSFL as a food ingredient into the modern food system, the functional properties of the proteins need to be fully understood. The term "functionality" in this context refers to "any property of food or food ingredient, except nutritional ones that influences its utilization" such as viscosity, water, and lipid absorption capacity, solubility, emulsification, gelling, and foaming capacity (Hall, 1996). Understanding the functional properties of BSFL will contribute to creating and stabilizing the structure of food products containing BSFL. Furthermore, it can also give a good indication of the best applications for its use as a food ingredient and potentially replace current functional food ingredients such as soya.

6.1 | Protein fraction

To date, there is very little information regarding the functionality of insect proteins in general, and even far less on BSFL proteins (Bußler et al., 2016; Omotoso & Adedire, 2007; Osasona & Olaofe, 2010; Womeni et al., 2012). To our knowledge, there is currently only one paper that has preliminary investigated the technofunctional properties of BSFL flour, defatted BSFL flour, and BSFL protein fractions (Bußler et al., 2016). The study investigated the effect of BSFL's high fat content on its functionality. It was found that the high fat content in the BSFL flours negatively affected the functionality of the BSFL flour and reducing the fat content of the BSFL through various fat extraction techniques was seen to improve some of the functionality of the proteins (Bußler et al., 2016). Furthermore, the solvent used in the fat extraction was found to have an effect on BSFL's protein quality and after comparing multiple solvents, 2-methyloxolane was found to produce a protein of better quality (Ravi et al., 2019).

BSFL have good lipid and water absorption capacities (Bußler et al., 2016), and these findings correlate well to that of other insect species, with studies indicating that they typically have high water and lipid absorption properties with some insect species having more desirable absorption properties than others (Omotoso & Adedire, 2007; Osasona & Olaofe, 2010; Womeni et al., 2012). The ability of proteins to absorb and retain both water and oil contributes to the overall taste, texture, and mouthfeel of food products such as in emulsified meat products and wheat doughs (Adebowale, Adeyemi, & Oshodi, 2005).

Foaming capacity in insects is typically found to be poor, with either unstable foams forming or none at all (Osasona & Olaofe, 2010; Womeni et al., 2012; Yi et al., 2013). To date, little is known regarding the foaming properties of BSFL, and although it can be assumed that BSFL would follow the same outcomes as other insect species, it is recommended to analyze and understand the specific foaming capacity of the BSFL. Gelation, another interesting functional property, has been detected in various insect protein fractions indicating that they have strong gelling capabilities as a potential alternative to gelatine in the food industry (Mariod & Fadul, 2015; Omotoso & Adedire, 2007; Osasona & Olaofe, 2010; Yi et al., 2013).

The current challenge in determining the functional properties of insects is the lack of standardization in protein isolation methods. Preliminary studies investigating the functional properties of select insect flours and proteins have found that the extraction method influenced the functionality of the extracted insect proteins (Amarender, Bhargava, Dossey, & Gamagedara, 2020; Bußler et al., 2016; Ravi et al., 2019). This was also seen to be true for BSFL, as it was established that the technofunctional properties of BSFL can be manipulated through processing and extraction methods (Bußler et al., 2016). Enzymatic hydrolysis using protease from *Bacillus licheniformis* was used to purify protein extract from insects and under controlled conditions has been seen to increase the technofunctional properties of mealworm proteins (Leni et al., 2020a). In this study by Leni and colleagues (2020), the percentage degree of hydrolysis (DH%) was seen to have a significant effect on the technofunctional properties of mealworm proteins, and longer hydrolyzation times led to a decrease in the functional properties of the mealworm proteins such as its emulsifying capacity. There are no other investigations using BSFL protein hydrolysates to compare it to and more data is required to compare the various extraction methods to optimize the processing parameters for BSFL hydrolysates with good technofunctional properties.

The challenge going forward is to improve the fractionation methods in order to yield optimum amounts of each BSF component (protein, fat, and chitin) while maintaining the functionality and integrity of each fractionated component (Caligiani et al., 2018). The challenge comes when separating the protein component from the chitin component (Woods, Goosen, Hoffman, & Pieterse, 2020). Alkali extraction tends to yield a higher protein fraction (96%) and a clean chitin component; however, the high protein yield is at the expense of the integrity of the proteins (Caligiani et al., 2018). Using an enzymatic protein extraction yielded approximately 60% protein with negligible damage to the protein, but there was some residual protein found in the chitin fraction (Caligiani et al., 2018). The killing method also has an effect on BSFL's protein extractability, and ultimately its functional properties. Blanching has resulted in a higher protein yield using milder extraction methods, less amino acid losses, and yields better results with enzymatic digestion than killing the larvae using freezing methods (Leni et al., 2019).

6.2 | Lipid fraction

The lipid portion of BSFL has recently been explored as a potential butter and margarine replacement, with up to 50% and 75% of BSFL lipids being successfully substituted into butter and margarine, respectively (Delicato et al., 2020; Smetana et al., 2020). Between 10 and 20 °C, BSFL margarine had high saturated fat contents, with a good stability, melting behavior, and spreading abilities comparable to conventional margarines (Smetana et al., 2020). Using a 75% BSFL lipid inclusion as a butter replacement had similar functionality to butter in that it did not affect the sponginess or crumbliness of cakes made using BSFL butter (Delicato et al., 2020). Although its use in food products is a good indication of its potential, further research is required into the chemical and physiochemical properties of BSFL fat for food production.

6.3 | Chitin fraction

Chitin from BSFL is a promising alternative to that from crustaceans, especially considering it is typically considered a by-product and would make a good side stream product. Industrial chemical methods that are used on crustaceans, namely, demineralization, deproteinization, and deacetylation, have been investigated to optimize the process to isolate and purify chitin from BSFL and convert it into its more usable derivative, chitosan. Chitosan yields from BSFL were found to be lower than that of crustaceans making it less economically viable until a stage where the process can be improved to obtain a higher yield (Hahn, Roth, Ji, Schmitt, & Zibek, 2020). Alternative methods such as enzymatic hydrolysis using proteases can be used as a more sustainable method for obtaining chitin from BSFL. Currently, this method is less efficient than the chemical method, but should it be optimized through more research it would yield better quality chitin, protein, and fat, without the chemical waste from chemical purification (Caligiani et al., 2018). Another less environmentally taxing method could make the use of eutectic solvents as a means to isolate and prepare chitin from BSFL; however, this method requires more research to validate its effectiveness and economic viability (Zhou et al., 2019). Further considerations going forward should look at the age of the BSFL, as it has an effect on the chitin content, thermal stability, and degradation rate of the chitin, as well as crystallinity all of which affect its end use (Wang et al., 2020). Chitin and chitosan derived from insects have demonstrated emulsion capabilities (Hirsch, Cho, Kim, & Jones, 2019) and antimicrobial properties (Shin, Kim, & Shin, 2019); however, further research into the possible uses of BSFL is still required, as chitin and chitosan are versatile ingredients and can be used in a wide range of industries from cosmetics, to medicinal, and to food (Kumar, 2000). The exact use and application of chitosan derived from BSFL holds great promise; however, it is yet to be fully investigated and implemented.

Understanding and using BSFL successfully as a functional ingredient in food applications could increase acceptability among consumers (Bußler et al., 2016). In order to achieve this, extensive research needs to be done in order to further understand which extraction method would optimize the functionality of each fraction, which would result in it being a versatile and economically viable food ingredient option (Caligiani et al., 2018).

7 | BSFL IN THE MODERN FOOD SYSTEM

Investigations around the aversion barrier toward eating insects have shown that cultural exposure plays an important role in acceptance of insects as a novel food source. Cultural exposure influences consumers' preference with regards to the kind of insect species eaten, the form the consumer would be willing to eat it in, their reasoning for eating it, or whether they would even eat insects at all (Hartmann et al., 2015; Tan et al., 2015). For example, Thai consumers who are unfamiliar with eating mealworms are repulsed by eating mealworms; however, this insect species is being popularized in Western countries, and as a result, Dutch consumers prefer products with mealworms (Tan et al., 2015). Thai consumers are motivated to eat insects due to their familiarity and taste, whereas Dutch consumers were motivated by sustainability, animal welfare concerns, and because of its novelty (Tan et al., 2015). Furthermore, Thai consumers preferred seeing the insects cooked in their whole form, and Dutch consumers preferred to have them disguised and not viewable in the dish at all. Much like the Thai consumers, a study on Kenyan consumers showed their preference for eating their culturally familiar termites, and their lack of willingness to consume mealworms, which they were unfamiliar with (Alemu & Olsen, 2018). Similar outcomes were found in a cross-cultural study between Chinese and German consumers, where Chinese consumers were more willing to eat insects, as a result of cultural familiarity, than the German consumers (Hartmann et al., 2015). This higher acceptance of processed and disguised insects among Western consumers has been seen in various studies, and as a result it is suggested that insects be disguised in products to improve their rate of acceptance (Gmuer et al., 2016; Hartmann et al., 2015; Schösler et al., 2012; Tan et al., 2015). With the global push for sustainable and healthy foods, the Western consumer is beginning to slowly accept insects as a food source. Investigations into the reasons and psychology behind the Western consumers' reluctance to eat insects focus on understanding and finding ways to try and change this mind-set (Gmuer et al., 2016; Hartmann et al., 2015; Ruby, Rozin, & Chan, 2015; Tan et al., 2015).

This information on how to change consumers mindset about eating insects can be used to develop strategies for introducing BSFL in the food space, such as incorporating BSFL into familiar food products in a manner where they are not visually seen (Hartmann et al., 2015; Schösler et al., 2012; Tan et al., 2015). Strategies for incorporating BSFL into food include fractionating the various components of BSFL to incorporate them as high-value ingredients in foods (Caligiani et al., 2018; Müller et al., 2017). Due to the versatility of BSFL, it has been included in a variety of applications such as incorporating BSFL flour into baked goods such as bread (González, Garzón, & Rosell, 2019), using BSFL fat as a butter or margarine replacement in baked goods (Delicato et al., 2020; Smetana et al., 2020) and using whole BSFL as a meat alternative in emulsified sausages (Bessa et al., 2019). Their comparable nutritional profile and low environmental footprint lend BSFL to become a desirable meat alternative (Bessa et al., 2019), and protein studies have found muscular proteins in BSFL, which further supports their potential use as a meat alternative (Leni et al., 2020; Rabani et al., 2019). Blind tastings have revealed that consumers think commercially bought insect patties compare well to commercial vegetarian patties; however, they still rate poorly in terms of texture and juiciness when compared to a commercial meat patty (Schouteten et al., 2016). Understanding and manipulating the flavor and texture is an important part of incorporating BSFL into the food system. Crude BSFL lipids were described as having "a strong and characteristic aroma" (Delicato et al., 2020) as well as a "fishy aroma" (Wang & Shelomi, 2017); however, the flavor was described more as an "earthy flavor" (Wang & Shelomi, 2017). There is limited information regarding the flavor and aroma of BSFL, and based on the information regarding the variability of the fatty acid composition, the flavor and aroma profile of the BSFL could be altered by harvesting at specific ages, selecting different feeds, and processing parameters (Caligiani et al., 2018). In terms of texture, BSFL margarine has a similar melting point and good spreading qualities comparable to conventional margarines, making it an interesting potential entry to market for BSFL as food ingredient (Smetana et al., 2020). Although the flavor and aroma of BSFL butter and margarine may not be comparable to conventional hard fat products, it has been suggested that deodorizing, a common application in the oil industry, be used to create a comparable BSFL fat to margarine in terms of organoleptic properties (Delicato et al., 2020). Using blanching to kill the larvae inactivates lipases, resulting in a stable lipid comprising mostly of triacylglycerols. Freezing on the other hand seems to stimulate lipase activity, releasing free fatty acids resulting in a less stable lipid, which would affect its potential applications and flavor (Caligiani et al., 2018). Other processing parameters also affect the visual appearance of BSFL. Killing the larvae through blanching as opposed to freezing results in a lighter brown color, due to the inactivation of enzymatic browning (Janssen et al., 2017; Leni et al., 2019; Yi, Van Boekel, & Lakemond, 2017). Defatting BSFL flours also contributes to a lighter brown color and a lower browning index, which can be more desirable in products than a dark brown powder (Bußler et al., 2016). All of these aspects have an effect on the perceived sensory quality and consumer acceptance. With taste being the biggest predictor of acceptance (Pambo, Okello, Mbeche, Kinyuru, & Alemu, 2018; Schouteten et al., 2016), defining and understanding the flavour characteristics of BSFL requires more in-depth research as this will ultimately determine whether BSFL will be accepted as food ingredient. A key element in further studies should include how the feed and larval age affects these sensory characteristics, especially as the feed has a direct impact on the fatty acid profile of the larvae (Barroso et al., 2017; Cullere et al., 2019; Ewald et al., 2020; Lim et al., 2019; Liu et al., 2019).

The focus on eating insects in the Western world needs to shift from a novelty food to one where it is portrayed as a normal and everyday food (Shelomi, 2015). Disgust may not necessarily based on the actual taste of the insects, but rather more on the perception and the history of eating a particular insect species (Ruby, Rozin, & Chan, 2015). Surveys on predominantly Western consumers have indicated that information regarding sustainability and nutrition of insects can increase consumers' willingness to eat a product containing insects and has the potential to be used as a tool to encourage consumers to try insect-based foods (Lombardi, Vecchio, Borrello, Caracciolo, & Cembalo, 2019; Pambo et al., 2018; Rumpold & Langen, 2019; Schouteten et al., 2016; Verneau et al., 2016); however, this cannot be assumed to be true for all consumers. A study in Germany found that of the three drivers of acceptance they were testing (sensation seeking, sustainability consciousness, and food disgust), sustainability consciousness was not found to be a big driver of potential acceptance for eating insects (Lammers, Ullmann, & Fiebelkorn, 2019). Similarly, a study in Australia found that positive information regarding eating insects was not enough to convince consumers to incorporate insects as a meat alternative (Sogari, Menozzi, & Mora, 2019). Although consuming BSFL, among other insect species, may be a controversial topic in the Western culture met with disgust and apprehension, cultural attitudes and preferences can change. In order to normalize BSFL, farmers and producers need to create and maintain a constant, inexpensive supply of BSFL-based products making them readily available for consumers to try at will (Shelomi, 2015; Sun-Waterhouse et al., 2016). BSFL has the potential to become an accessible and inexpensive insect species; however, there needs to be a strong drive to shift their role from only an animal feed option to that of a viable human food source. Taste exposure and innovative product development can assist in changing the preconceived ideas consumers have toward the appropriateness, and sensory properties of BSFL (Tan et al., 2016). Physically having access to and tasting insect products can be a powerful tool to reduce food neophobia, as well as create familiarity regarding the tastes and textures associated with eating insect-based foods (Caparros Megido et al., 2016; Pambo et al., 2018; Park & Cho, 2016; Sogari, Bogueva, & Marinova, 2019). Using a combination of positive information and tasting BSFL-based products can be used as a strong strategy to encourage the consumption of BSFL among consumers. It is important to incorporate BSFL into appropriate food products to encourage regular consumption of BSFL that would be considered to be appealing once the novelty of eating insects has subsided (Tan et al., 2016). Ultimately, the success of BSFL as a food product will be determined by their appropriateness in food products and their desirable sensory properties in these products, as this will increase the likelihood of repeat purchases by consumers (Pambo et al., 2018; Schouteten et al., 2016; Tan et al., 2016).

8 | CONCLUDING REMARKS

BSFL as a food source has the potential to provide a sustainable, nutrient dense, and cost-effective protein, lipid, and chitin alternative. Insect consumption in Western societies is still a novelty, with only a select few edible insect species to choose from. Despite all the promising information about BSFL as a viable protein alternative, to date it has largely been considered an animal feed, potentially making consumers less willing to eat them as food as well as leaving a large gap of knowledge with regards to utilizing BSFL successfully as a food ingredient. The largest concern at this stage is the food safety risk associated with using BSFL grown on "waste," and therefore more research is required into the food safety of consuming BSFL before fully advocating its consumption. Research into the kinds of substrates as well as the processing parameters is required to ensure that BSFL fulfils global food safety criteria. This information will feed directly into creating legislation to regulate the use of BSFL for human consumption, which will in turn make consumers more comfortable consuming them. Understanding the functional properties of BSFL will allow for optimization of processing parameters to ensure that products of good quality and sensory properties can be produced, which is the most important aspect determining consumer acceptance. Last, the farming of BSFL specifically for human consumption needs to be developed and optimized to create a low-priced, safe, and standardized supply of BSFL that will make the development and use of BSFL desirable in the food industry.

AUTHOR CONTRIBUTIONS

Leah Bessa wrote and submitted the manuscript with input on content and literature sources from Louwrens Hoffman, Jeannine Marais, and Elsje Pieterse. All authors contributed to reviewing this work. Final edits were done by Leah Bessa and Louwrens Hoffman.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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