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Rethinking food waste: Exploring a black soldier fly larvae-based upcycling strategy for sustainable poultry production

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ABSTRACT

Food waste (FW) contributes to greenhouse gas emissions, burdens waste management systems, worsens food insecurity, and reduces biodiversity. Consequently, upcycling strategies must be refined to efficiently convert FW into valuable products. The utilization of black soldier fly larvae (BSFL) to convert FW into nutrient-rich insect meal for use in poultry diets is one such nascent strategy. This upcycling strategy has the potential to address food security challenges while reducing environmental impacts of both FW and poultry production systems. Indeed, innovations in BSFL production and the abundance of FW means that this strategy has a high potential for adoption and scaling up, despite a regulatory framework that lags in several countries. We analyse the suitability of various FW streams for BSFL and the insect's nutraceutical value for poultry. This strategy can resolve the global FW problem while contributing towards sustainable food production systems with minimal recourse to additional planetary resources.

1. Introduction

According to the World Food Program (WFP), approximately 40% of food meant for human consumption is lost or wasted every year, equating to roughly 1.3 billion tons globally (WFP, 2020). Food waste (FW) contributes to greenhouse gas (GHG) emissions, burdens waste management systems, worsens food and nutrition insecurity, and plays a role in loss of biodiversity (UNEP, 2021). In addition, FW disposed in landfills and open dumps is a breeding ground for disease vectors while producing additional GHGs and other atmospheric and hydrospheric pollutants (Kaza et al., 2018). Given that food loss and waste is expected to double by 2050 (Lopez Barrera and Hertel, 2021), a major shift from disposal to prevention, recycling, and upcycling strategies is imperative for sustainable management of FW. Despite broad political and social consensus on the need to reduce FW, there is evidence that the world has fallen far behind in its attempt to halve this waste by 2030 (WRI, 2021). There is a clear need for innovative recycling and upcycling strategies to mitigate the problem of FW, and with it, the attendant negative economic and environmental impacts.

In this review, we explore the utility of a two-stage upcycling strategy, wherein FW serves as a substrate to produce black soldier fly larvae (BSFL) in the first stage. Subsequently, these larvae are employed as a nutrient source for intensively reared poultry in the second stage. Upcycling FW using insect larvae has several advantages that include low space and energy requirements as well as environmental sustainability (Fowles and Nansen, 2020). The BSFL-based bioconversion of FW to produce feed ingredients for poultry is a marketable, sustainable, and potentially effective solution to the problem of FW. However, there are several challenges that need to be addressed such as suitability of various FW streams, optimum inclusion levels of the insect meal in poultry diets, inconsistent impact on quantity and quality of poultry products, consumer acceptance of products from BSFL-fed chickens, and lack of enabling regulatory and policy frameworks. Insects are known to efficiently convert large quantities of FW into useful products such as human food, animal feed, fertilisers, biofuels, and pharmaceuticals (Fowles and Nansen, 2020). Using BSFL reared on FW as an alternative protein source in poultry diets could be a sustainable upcycling strategy, especially in regions where soybean cultivation is unsuitable. The

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review presents the state-of-the-art on the role of BSFL as an upcycling agent of FW; environmental and economic benefits of FW bioconversion; nutritional aspects of BSFL as a poultry feed ingredient; as well as challenges and opportunities for the implementation of the proposed two-stage upcycling strategy. The BSFL-based two-stage upcycling approach has the potential to transform FW into nutrient-dense poultry products that contribute to improved global food and nutrition security of a growing human population. In addition, this strategy ensures that poultry production systems have lower environmental impacts, compete less for resources with humans, and are resilient to the frequently occurring climate perturbations. This proposed transformation of existing poultry production systems as tools for FW upcycling enables the sustainable supply of nutritious diets to a growing human population without excessive recourse to additional planetary resources.

2. Management strategies for food waste

Management strategies such as microbial fermentation, composting, recycling into animal feed, and upcycling to generate value added products have been used to divert FW from landfills and incineration facilities. The attributes and limitations of these FW management strategies are summarized in Table 1.

2.1. Landfilling and incineration

In several countries, a large proportion of FW ends up in landfills resulting in adverse environmental effects (WWF, 2017) such as bad odours, soil, air, and water contamination with the risk of human disease transmission (Chew et al., 2019). Other challenges may include high transportation costs, leachate production leading to groundwater contamination, and congestion due to limited land for landfill sites (Nahman et al., 2012). Incineration is another strategy used to manage FW with or without energy recovery (Raksasat et al., 2020). A major drawback is the production of toxic pollutants (CO_2, NO_x and ash residue) upon FW incineration (Raksasat et al., 2020). While landfilling and incineration remain common, these traditional FW management practices are expensive and are not necessarily designed to recycle nutrients and energy in waste and thus are largely economically, environmentally, and socially unsustainable.

2.2. Microbial fermentation

Methods such as solid-state fermentation (SSF), lactic acid fermentation, or alcoholic fermentation use specific microorganisms to produce value-added bioproducts and modify FW thus enhancing its nutritional value for animals while reducing its environmental impact (Yafeto et al., 2023). Another microbe-based method is anaerobic digestion where organic waste materials are decomposed in the absence of oxygen (Raksasat et al., 2020) to produce biogas and digestate. This strategy embodies the circular economy concept by reclaiming valuable resources (biogas and digestate) from FW and reintegrating them into the energy and agricultural sectors, thus reducing the need for new resources. However, the limitations for microbial fermentation strategies include the need for a controlled environment to promote microbial activity (Braguglia et al., 2018), which may increase the cost of FW management. In addition, some FW streams will require costly

Table. 1
A summary of benefits and limitations of some common food waste (FW) management strategies.

Strategy	Definition	Benefits	Limitations	References
Landfilling	Disposal of FW in designated landfills	• Simple and cost-effective • Requires minimal infrastructure • Only option for non-recyclable and non-compostable waste	• Methane emissions during decomposition • Space constraints • Groundwater and soil contamination/pollution • High transportation costs • Air pollution and bad odour	Chew et al. (2019) Nahman et al. (2012)
Incineration	Controlled burning of FW for energy.	• Reduces waste volume • Source of energy that can be used to generate electricity	• High energy costs and greenhouse gas emissions during combustion • Air pollution and emission of harmful substances	Raksasat et al. (2020)
Microbial fermentation	Microbial decomposition of FW	• Methane production for energy generation. • Lowers greenhouse gas emissions from FW • Nutrient-rich digestate: soil amendment • Reintegrates nutrients into energy and agricultural sectors • Nutrient-rich, more digestible animal feed with lower levels of antinutritional factors	• Specialized infrastructure and equipment required • Requires controlled environment to promote optimal microbial activity • Not all FW streams are suitable for anaerobic digestion	Braguglia et al. (2018) Raksasat et al. (2020) Yafeto et al. (2023)
Composting	Decomposition of FW into compost under controlled aerobic conditions	• Produces nutrient-rich compost for soil improvement • Diverts FW from landfills and reduces methane emissions • Supports sustainable agriculture	• Requires proper segregation of FW • Not suitable for large quantities of FW • Process requires time and space • High capital and transportation costs • Air pollution and bad odour	Awasthi et al. (2020); Palaniveloo et al. (2020)
Re-use as animal feed	Feeding FW directly to food animals	• FW reduction by utilizing it as a nutrient source • Reduces feed costs for farmers • Provides an immediate solution to FW	• Risk of spreading diseases if not properly processed • Quality control requirements are high • Regulatory restrictions on what can be fed to animals	Georganas et al. (2020); Zamli et al. (2021)
Upcycling using insects	Using FW streams as feedstock for valuable insects	• Efficient conversion of FW into high-protein insect biomass • Reared insects can be used in animal feed or even human consumption • Reduces FW and pressure on natural resources	• Requires insect farming facilities • Acceptance and awareness of insect-based products is still low • Research and development needed for scalability and regulatory approval	Singh and Kumari (2019); Surendra et al. (2020); Ravi et al. (2020)

pre-treatments to increase rate of decomposition and maximize biomass reduction.

2.3. Composting

Composting refers to a natural decomposition process under controlled aerobic conditions whereby FW are reduced to their simplest components by microorganisms (Palaniveloo et al., 2020). Effectiveness of composting depends on oxygen supply, moisture content, temperature, pH, particle size, carbon-to-nitrogen ratio (C/N), and degree of compaction (Cerda et al., 2018). This strategy is considered the least environmentally sustainable for reducing FW due to bad odours, some gaseous emissions, and leachate generation (Awasthi et al., 2020). However, co-composting is more valued because it relies on the use of different FW substrates and other additives thus providing an ideal composting environment (Awasthi et al., 2020). For example, Nguyen et al. (2023) reported that co-composting a catering services FW mixture [vegetables and fruits (47 %), tea leaves (16 %), and red meats (29 %)] with wood chip biochar significantly reduced H_2S and NH_3 emissions while enhancing compost maturity. However, composting may be relatively expensive as it requires high initial capital investment, storage and transportation costs, and land (Palaniveloo et al., 2020). In addition, it is a lengthy process, potentially taking up to 3 to 4 months for a small-scale operation (Chew et al., 2019).

2.4. Recycling into animal feed

Food waste can be recycled and used directly as safe animal feed (Boumans et al., 2022). A major limitation of this approach is the high consumption of energy during the dehydration process (Georganas et al., 2020), which is necessary for nutrient analysis and subsequent diet formulation. However, dehydration of FW can be achieved through mechanical compression to squeeze out excess liquid followed by solar drying. Solar drying can be a cost-effective and widely accessible solution in the long run (EL-Mesery et al., 2022). However, the compression step necessitates specific equipment, may not be readily accessible, can raise energy demands, and might lead to a notable loss of nutrients in FW. Recycling into animal feed typically involves collection of FW and removal of non-food items followed by a pre-treatment and processing step where the organic waste may be dried, ground to reduce particle size, and/or treated to enhance digestibility (Boumans et al., 2022). This would be followed by a laboratory analysis to establish the nutrient density of FW and blending with other feed ingredients to produce a final diet that meets the nutritional requirements of the target animal. Other processing methods may include cooking, extrusion, pelletizing, dehydration, ensiling, and probiotic treatment (Georganas et al., 2020). Food waste recycling challenges include the possible presence of antibiotics, salt, mycotoxins, pesticides, heavy metals, biogenic amines associated with microbial activity, and non-food contaminants (plastic, glass, metal, etc.) (Georganas et al., 2020; Zamli et al., 2021).

2.5. Upcycling of food waste using black soldier fly

The transformation of FW into products or material of higher quality, value, or functionality often creating novel, innovative, and premium products (adding value) is referred to as upcycling (Ravi et al., 2020). This can be achieved through several strategies including microbial fermentation and insects such as BSFL. In this review, converting FW into BSFL for use as a nutrient source in poultry diets is presented as a key upcycling strategy. The production of nutrient-dense poultry products (meat and eggs) represents sustainable value-addition where nutrients are recovered from FW and redirected into the food chain. Upcycling of nutrients from FW into valuable poultry products for human nutrition is a four stage process, which includes: 1) FW selection (larval dietary requirements may be met through blended waste substrates or fortification with supplemental nutrients), 2) larval FW conversion (nutrients in FW are converted into chitin, carbohydrates, lipids, proteins, and organic acids), 3) transfer of larval nutrients to poultry (BSFL-containing diets are formulated), and 4) human consumption of poultry products (Ravi et al., 2020). However, there are cost constraints associated with BSFL upcycling of FW arising from transportation and energy requirements (Singh and Kumari, 2019). Other challenges include chemical and microbial contaminants present in FW that could easily be transferred to BSFL and poultry products as well as policies and regulations that may limit the expansion and the use of different insect species (Surendra et al., 2020).

3. Distribution and life cycle of the black soldier fly

The black soldier fly (BSF) is the most widely distributed species of the *Hermetinae* sub-family under the order Diptera. Its spread and distribution in palearctic (South-Eastern Europe, Middle East, Austria, Belgium, and the United Kingdom etc.) is attributed to its introduction as a biological agent against houseflies in farms and stables (Demetriou et al., 2022). The spread of BSF to other parts of Europe could be attributed to migration aided by biotic or abiotic factors such as human action and winds. The lifecycle of the BSF consists of eggs, larvae, pupae, prepupae, and adult stages (Fig. 1). The female lays eggs, which hatch into the neonate larvae within four days. The broad feeding habits and voracious appetite of the neonate larva makes it an important agent for use in bioconversion of FW. Indeed, the BSFL can utilize kitchen waste, fruits, vegetables, and brewers' spent grain as nutrient sources (Nguyen et al., 2015; Shumo et al., 2019), amongst other food sources. The larvae cease feeding upon reaching the pre-pupal stage (mature size).

The pre-pupae empty their digestive tracts, leave the food source, and migrate to dry locations to undergo pupation. At the pupae stage, the larvae is composed of 43.8–46.2 % protein and 7.2–8.2 % fat content on a dry matter (DM) basis (Liu et al., 2017). In about 14 days, the pupae transform into adult BSF, which does not feed but uses stored fat as an energy source for maintenance and production. The fly does not bite or transfer diseases because it does not have a stinger, mouth parts, or digestive organs. Overall, the BSF's lifecycle ranges from 2 to 4 months depending on feed availability, and prevailing environmental conditions.

4. Impact of substrate on black soldier fly larvae growth and development indices

Growth and development of BSFL is heavily influenced by the physicochemical characteristics of its substrate such as chemical composition, porosity, density, ratio of solids to liquid fractions, moisture levels, particle size, and formulation (ground, solid or liquid) (Alyokhin et al., 2019). In addition, the suitability and preferability of substrates depends on the age, behaviour, and physiological status of BSFL (Beesigamukama et al., 2021). Substrates with excess fibre content (e.g., fruit and vegetable pulp, whole grains, grain residues, etc.), high moisture content (expired milk, expired beverages, molasses, etc.), and unbalanced nutritional composition negatively affects growth and development of BSFL (Alyokhin et al., 2019). High quality feedstuffs are vital for the growth and development of BSFL because they reduce larval development time and increase growth rates (Broeckx et al., 2021) and nutrient composition. The impact of some substrates on development and growth indices of BSFL is summarized in Table 2.

4.1. Larval development time

Larval development refers to the length of time it takes for larvae to reach the pre-pupal stage or full maturity, a parameter that is highly depended on type of substrate used. For example, shorter larval development times have been reported for BSFL reared on substrates with moderate protein (∼ 18 % DM) and moisture content (>50 %) (Tschirner and Simon, 2015). The demand for high dietary moisture by

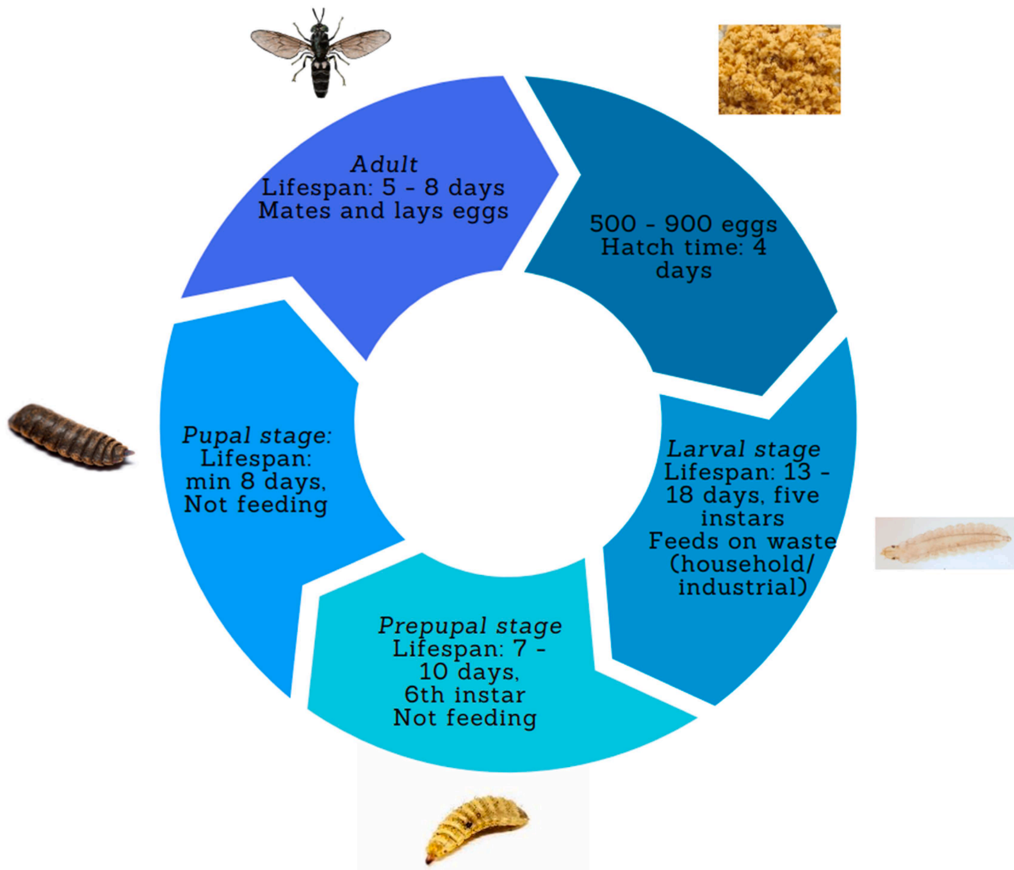

Fig.. 1. Lifecycle of the black soldier fly.

BSFL could be due to the relatively small morphology of its mouthparts, which resemble scavenging insects and rely on scraping the surface of substrates to obtain nutrients. The larval development time reported for BSFL on a blend of brewers' spent grain and trub was significantly lower (18.7 days) compared to those reared on the brewers' spent grain alone (24.7 days) and chopped spent grain (33 days) (Jucker et al., 2019). The longest larval development was reported by Oonincx et al. (2015) for BSFL reared on ground chicken, cow, and pig feed substrates (144 and 214 days), a consequence of reduced nutritive value due to the destruction of heat-labile nutrients in the substrate. It is, therefore, important that substrate processing methods, larval stage, and feeding regimes be carefully considered for optimal development time for BSFL.

4.2. Larval yield

Tschirner and Simon (2015) reported that distillers' grains with solubles and dried sugar beet pulp promoted the lowest larval yields in BSF compared to the control (mixture of cereal middlings). This was attributed to the higher protein content of distillers' grains (31.2 % DM) and high fibre content of beet pulp (15.6 % DM) compared to the control diet that had lower crude fibre (3.1 % DM) and protein (23.8 % DM) content. When reared in protein-rich substrate, BSFL needs to eliminate excess nitrogen in the form of ammonia through an energy-intensive detoxification process (Danieli et al., 2019). This process diverts dietary energy from production processes to maintenance (Tschirner and Simon, 2015) thus reducing larval yields. In a related study by Beesigamukama et al. (2021), brewer's spent grain ($C/N = 11$; control) was amended with sawdust to produce BSFL substrates with C/N ratios of 15, 20, 25 and 30. Larval yield from the control was similar to that of sawdust-amended substrate with C/N ratio of 15, but higher than in substrates with higher C/N ratios (Beesigamukama et al., 2021). The higher fresh and dry larval weights from the control and amended substrate ($C/N = 15$) could be attributed to their lower N content thus confirming reported deleterious effects of excess protein in BSFL substrates.

Nyakeri et al. (2017) observed lower larval yields from fibrous feed substrates (banana peels) compared to less fibrous food waste (brewer's waste and faecal sludge). Physicochemical characterization of banana peels has shown that it contains high insoluble fibre fractions (Agama-Acevedo et al., 2016), which can reduce the growth of BSFL through reduced feed intake and nutrient digestibility. In addition, it was reported that BSFL crawl out of the banana peels due to discomfort caused by the presence of fibre in the peel, thus explaining the low larval yield relative to other feed substrates (Nyakeri et al., 2017). Larval yield is also influenced by the quantity of feed consumed. Indeed, Nyakeri et al. (2019) found that the BSFL larval yield increased from 124 to 190 mg, as the daily feeding of faecal sludge increased from 140 to 250 mg.

4.3. Survival rates

The lowest survival rates have been reported for BSFL reared on protein-rich substrates such as milk whey (15 %) and fish scraps (21 %) compared to low protein substrates such as bread dough (34 %) and undigested sludge (39 %) (Hadj Saadoun et al., 2020). Lower carbohydrate content in protein-rich substrates coupled with the toxicity associated with high protein levels are the possible reasons for lower BSFL survival rates (Meneguz et al., 2018). Adebayo et al. (2021) found that increasing protein content in substrates produced BSFL with smaller size and weights. Accordingly, a 7 % protein content (DM) in substrates has been suggested for optimum development of BSFL (Broeckx et al., 2021). Insects are also known to convert dietary carbohydrates into lipids more efficiently than dietary proteins (Danieli et al., 2019). Lipids in BSFL are

Table. 2
Influence of selected substrates on growth and development indices of the black soldier fly larvae.

Substrate type	Parameter	Impact of substrate	References
Brewers' grains	Development time	Reduced larval development time due to high protein and moisture content.	Broeckx et al. (2021)
A blend of brewers' by-products, whole and chopped spent grains	Development time	Brewers' by-products blend had the shortest BSFL development time compared to the sole spent grains, signifying that substrate formulation affects BSFL developmental time.	Jucker et al. (2019)
Ground chicken, cow, and pig feedstuffs	Development time	Powdered substrate increased larval development time due to loss of nutrients. Development time ranged between 144 and 214 days, which is well-above the average of 13 and 60 days.	Oonincx et al. (2015)
Distillers' grain pulp and dried sugar beet pulp	Larval yield	Both substrates produced the lowest yields compared to the control (mixture of cereal middlings) due to their high protein and fibre content.	Tschiner and Simon (2015)
Bananas peels, food waste, brewers' waste, and faecal sludge	Larval yield	Banana peels promoted the lowest larval yield compared to food waste, brewers waste, and faecal sludge. Low yields in banana peels are due to the high fibre content that causes discomfort to BSFL resulting in them crawling out of the substrate.	Nyakeri et al. (2017).
Protein rich (milk whey and fish scraps) Low protein (bread dough and undigested sludge)	Survival rate	Higher protein diets had lower survival rates and larval yield compared to low protein diets. Due to low carbohydrates and excess protein in milk whey and fish scraps: larvae need to eliminate excess nitrogen through an energy-intensive detoxification process - diverts energy from production processes thus slows down growth and development.	Hadj Saadoun et al. (2020)
Blended ground corn	Survival rate	Blended ground corn reduced BSFL survival rates due to loss of nutrients that occur during grinding or processing of feed substrate.	Danieli et al. (2019)
Winery by-products	Survival rate	Low BSFL survival rates because of polyphenols and pesticides, which are harmful to BSFL.	Meneguz et al. (2018).
Degassed sludge	Survival rate	Low BSFL survival rates (< 50%) due to lack of protein and carbohydrates: low-quality substrate.	Lalander et al. (2019)
Fish waste Kitchen waste	Larval weight	Fish waste reduced larval weights because it contains heavy metals and high protein content. Kitchen waste increased the larval weight compared to fish waste due to its high calorie and fat content.	Nguyen et al. (2015)

important because they provide the adult fly with sufficient energy reserves while preventing dehydration (by reducing transpiration and storing non-imbibed water), a critical function because insects have an open body system. Degassed sludge had an imbalanced nutritional composition (lower protein and carbohydrate content) resulting in less than 50 % BSFL survival rate (Lalander et al., 2019).

Low survival rates were also reported for BSFL reared on blended ground corn and winery by-products (Danieli et al., 2019; Meneguz et al., 2018). This was attributed to the loss of nutrients that occurs during the grinding/processing of feed substrates. Furthermore, winery by-products contain polyphenols and pesticide residues, which are harmful to the BSFL (Meneguz et al., 2018). Fibrous FW substrates could benefit from pre-treatments using physical, biological, and chemical techniques or through blending with higher quality feed substrates as discussed above. These treatments have been shown to improve the nutritional composition of the FW substrates by altering the structure and/or reducing indigestible components, making more nutrients accessible to the BSFL. They can also improve FW substrate digestibility, thereby aiding growth and development as well as the survival rate of BSFL.

4.4. *Larval weight and size*

The typical weight of BSFL has been reported to range between 55 and 299 mg, with a few studies reporting weights above 299 mg (Bekker et al., 2021). Lower larval weights have been reported on fibrous substrates because larvae have low feed intake and tend to crawl out of high-fibre substrates (Nyakeri et al., 2017). Furthermore, BSFL reared on heavy metal-rich substrate such as fish waste tend to have lower larval weights due to toxicity (Nguyen et al., 2015). It is, however, important to note that fish wastes vary in terms of heavy metal content and thus should not be excluded from BSFL rearing without appropriate chemical characterization. On the other hand, Nguyen et al. (2015) found that kitchen waste produced the heavy BSFL due to its high calorie and fat content, suggesting that this FW stream could be prioritized in the two-stage upcycling strategy.

Bellezza Oddon et al. (2022) suggested that BSFL with longer development times tend to have heavier weights and have likely accrued sufficient body reserves to support their adult stage. Liew et al. (2022) found that larvae reared for 24.7–33.0 days had higher weights (0.860–0.874 g) compared to those reared for 15.3–18.7 days (0.235 to 0.244 g). Similar findings have been reported by Spranghers et al. (2017). In contrast, other studies (Adebayo et al., 2021; Broeckx et al., 2021) have demonstrated that BSFL reared on high quality feedstuffs tend to have shorter development phases and higher weights. For example, BSFL reared on chicken feed recorded the highest weight (0.30 g), length (2.18 cm), and shortest development time (21 days) (Adebayo et al., 2021). This suggests that larval weight is primarily a function of substrate nutrient density.

5. Attributes of black soldier fly larvae as a food waste bioconverter

The BSFL have several attributes that make them suitable bioconverters of FW and agents for the transfer of nutrients from FW to animal products suitable for human consumption. These attributes are summarized in Table 3.

6. Optimizing food wastes for black soldier fly larvae

6.1. The nutritional ecology of the black soldier fly

Successful insect rearing depends on several factors, which include the composition and consistency of insect feed, type of insect, and rearing conditions (Ojha et al., 2020). The chemical and physical properties of FW substrates are especially important because they must match the feeding behaviour, morphological features, and nutrient requirements of the target insect. While BSFL has a very wide substrate range, not all FW streams are equally available or suitable for efficient larval growth. Indeed, FW streams with high hemicellulose and lignin content are unlikely to support high levels of waste conversion efficiency, final larval weight, larval survival, and waste reduction efficiency (Isibika et al., 2019). The nutritional composition of FW substrates influences growth rate, larval weight, survival rate, and nutritional composition of insects (Siddiqui et al., 2022) such as BSFL. A common challenge for household and industrial FW streams is high salt content, which has been experimentally demonstrated to decrease larval weight and pupation ratio in BSF (Cho et al., 2020).

Several strategies have been employed to optimize substrates for growth, survival, biomass yield, and nutrient composition of BSFL with varied results. These strategies should be used to maximize the quantity and quality of FW as substrates for BSFL rearing. They include physical (e.g., heat, grinding, milling, gamma irradiation, electron beams, or microwaves), chemical (e.g., alkali or acid solutions), and biological (e.g., microbial fermentation, or enzymes) pre-treatments (Norgren et al., 2021), provision of supplemental nutrients and blending contrasting FW streams. The main objectives of these pre-treatments include enhancing the surface properties of FW thereby enhancing microbial interactions, improving the rate of hydrolysis of complex carbohydrates, proteins, and lipids, and increasing accessibility of intractable components of the substrates for better degradation and use by the insect larvae (Zafar et al., 2022). Supplementing (fortification) nutrients that could be low in FW substrates is yet another method to optimize, not only the biodegradation process, but also the nutrient density of larvae produced. It is unlikely that any FW mono-stream would contain all the nutrients required to support optimal BSFL growth and nutrient composition. A chemical characterization is, therefore, essential given that chemical composition of a FW mono-stream, even from the same source, could vary greatly (Poe et al., 2020). It is important to note that optimizing FW for BSFL cultivation has cost implications and a cost-benefit analysis must always be carried out to ensure economic viability.

Table. 3
Attributes of black soldier fly larvae as a bioconverter of food waste and a nascent nutrient source in poultry feed.

Attribute	References
Can tolerate dietary ingredients potentially harmful or indigestible to other fly species	Seyedalmoosavi et al. (2022)
Omnivorous: can be cultured on blended streams of organic FW substrates of plant and animal origin	Grossule et al. (2023)
Superior feed conversion ratio: consumes 2 – 6 times body mass/day, convert up to 42–75% of biowaste into high protein biomass	Seyedalmoosavi et al. (2022)
High survival rate (97 to 100%) on mixed FW streams; not a disease vector	Siddiqui et al. (2022)
Reduces or inactivates harmful pathogens (e.g., *Escherichia* sp., *Salmonella* sp., *Vibrio* sp., *Yersinia* sp., etc.) and degrades synthetic pharmaceuticals and pesticides	Surendra et al. (2020)
Produces antimicrobial peptides and lauric acid, potential transfer to animal products	Manniello et al. (2021); Suryati et al. (2023)
Rich in digestible proteins, fats, chitins, antimicrobial peptides, vitamins, and selected minerals	Manniello et al. (2021)
Higher concentration of most amino acids than soybean	Seyedalmoosavi et al. (2022)
Bioconversion of FW is not compromised by bioplastics	Grossule et al. (2023)
Not commonly reared for human consumption eliminating direct competition with farmed animals	Seyedalmoosavi et al. (2022)

6.2. Fortification

Fortification is a strategy whereby BSF feedstock is supplemented with either pure nutrients or plant or animal nutrient sources to enhance growth performance and/or nutrient composition of larvae. In practice, larval growth is improved through the careful formulation of FW substrates by adding macro- and micro-nutrients to address any deficiencies. Blending different FW streams would be the most practical and less expensive approach. For example, small quantities of seaweeds or fish offal could be added to carbohydrate-rich or terrestrial animal tissue FW to increase the level of polyunsaturated fatty acids (PUFA). This will ensure that PUFA levels are also high in the produced larvae, an important nutritional outcome if the BSFL is to be used as a protein and lipid source in fish diets. Indeed, Truzzi et al. (2020) produced BSF prepupae with higher nutritional indices, especially omega-3 PUFAs, when coffee silverskin waste (product of the coffee-roasting industry) was supplemented with the microalgae, *Schizochytrium* spp. at 10, 20, and 25 %. Blending of FW streams and supplementation is designed to achieve a balanced feedstock that promotes efficient waste bioconversion, rapid insect growth and produces nutrient-rich BSFL. In a study by Li et al. (2021), blending soybean curd residue (30 %) and kitchen waste (70 %) promoted the highest BSF larval biomass (11.4 g DM) and larval crude lipid content (45.9 %) and lowest feed conversion ratio (FCR) (2.51) compared to individual substrates. Similarly, Singh et al. (2021) demonstrated that mixed FW (kitchen, fruit, restaurant, and vegetable wastes) promoted the highest biowaste reduction efficiency of 72 %, followed by fruit, restaurant, and vegetable wastes in that order.

6.3. Chemical treatment

This approach is particularly useful for FW streams that are high in lignin and cellulose such as fruit pomaces, whole grains, and psyllium husks commonly used as fibre supplements in human diets. For these FW streams, chemical pre-treatments are usually designed to reduce the concentration of the lignocellulosic compounds, that are quite resistant to depolymerization thereby enhancing BSFL performance (Behera et al., 2014). The treatments increase the bioavailability of nutrients through increased accessible surface area, reduced crystallinity of cellulose, transformation of carbohydrates, proteins, and lipids into more digestible nutrients, alteration of lignin structure, degradation and denaturing of antinutrients, increasing sugar content as well as reducing particle size (Norgren et al., 2021). Chemical approaches for high fibre FW streams employ oxidizing agents (e.g., hydrogen peroxide), acids, alkalis, and ozone to break down lignin and/or hemicelluloses (Peguero et al., 2022). Common alkaline pre-treatments include sodium hydroxide, potassium hydroxide, calcium hydroxide, and aqueous ammonia (Zafar et al., 2022). Acid treatments involve the use of hydrochloric acid, sulfuric acid, and acetic acid to hydrolyse hemicellulose and other biopolymers to render them susceptible to enzymatic degradation (Zafar et al., 2022). The drawback with using high concentrations of acids and alkalis is their corrosiveness, which requires a setup that is resistant to corrosion as well as a neutralizing agent to increase the pH prior to using the substrate (Sun and Cheng, 2002). There are also cost implications related to the use of chemical treatments while safety concerns are high.

6.4. Physical treatment

Mechanical pre-treatment can reduce substrate particle sizes thereby increasing the surface area to volume ratio of FW (Zafar et al., 2022), resulting in better utilization of substrate by insect larvae. However, these technologies are considered suitable for substrates with low moisture content (< 15%), while colloid mill extruders and expanders are for substrates with moisture content between 15–20 % (Peguero et al., 2022). Other physical treatments include several kinds of radiation such as ultrasound, microwaves, electron beams, and gamma rays that can aid the hydrolysis of FW (Banu et al., 2020). Ultrasound, despite being energy inefficient, has been shown to promote the enzymatic degradation of starchy crops, such as cassava, corn, and triticale (Zafar et al., 2022). The drawbacks for using physical treatments to optimize FW for BSFL are the high capital and energy costs while considerable amounts of recalcitrant products can be generated (Banu et al., 2020). The effectiveness of heat treatments is dependant on temperature, time, and, in some cases, pressure. Temperatures above 100 °C and processing times ranging from 15 to 120 min at 2–9 bars of pressure have been recommended (Kamal et al., 2022). However, this approach may not suit FW substrates for BSFL production because of possible reduction in the numbers of beneficial microorganisms present in FW (Peguero et al., 2022).

6.5. Biological treatment

Biological treatments are important in preparing FW as a feedstock for BSFL because they can improve the nutritional quality and safety of the substrate while creating a more favourable environment for larval growth and development (Zafar et al., 2022). Unlike physical and chemical optimization treatments, biological approaches require less energy and do not use chemicals. However, the rate of decomposition may be too slow if fermentation parameters are not carefully optimized. Pre-fermentation helps in enhancing the digestibility and bioavailability of nutrients to the larvae as most nutrients in raw FW are found in an insoluble form (Ojha et al., 2020). These treatments employ bacteria, fungi, yeasts, or mixtures of microorganisms as additives to FW substrates. The microbial additives may also reduce the levels of anti-nutritional factors such as lignin, tannins, trypsin inhibitors or cellulose (Isibika et al., 2019). A few studies have investigated the utility of biological treatments in optimizing FW for insect bioconversion. For example, Lu et al. (2023) used ten strains of yeast to modify cooked university canteen FW (rice, noodles, eggs, tofu, and vegetables, meat, and fish products) and increased (82.3–115.5 %) larval fatty acid yields. Isibika et al. (2019) showed that banana peel substrates treated for 14 days with Rhizopus oligosporus produced heavier larvae (>150 mg per larva) compared to untreated substrates (134 mg per larva). Similarly, Lindberg et al. (2022) pre-treated a fruit peels and vegetable waste blend with *Trichoderma reesei* for 14 days and used the product as BSFL feedstock, resulting in 84 and 60% more biomass reduction of the trimmings and peels, respectively. This suggests that fungal pre-treatment of vegetable materials increased nutrient bioavailability for the larvae. There is sufficient evidence that biological treatments are a viable option for the optimization of FW substrates for BSFL production in the two-stage upcycling strategy. These treatments would allow a diverse range of FW streams to meet the nutritional demands of the BSFL and, hence, poultry species.

7. Nutraceutical value of black soldier fly larvae for poultry

7.1. Nutritional value of black soldier fly larvae

Insect meals, especially BSFL, have long been considered as strong candidates for the replacement of both plant and animal-based dietary proteins for a variety of food producing animals including poultry. Indeed, the BSFL is high in protein, fat, and minerals (Marono et al., 2017) hence the growing interest in its use as a nutrient and bioactive compound source in poultry diets. Numerous studies have evaluated the feed value of BSFL in poultry, with Shumo et al. (2019) reporting that BSFL had higher biological protein value than soybean and fishmeal. In addition, it has been revealed that BSFL possesses a well-balanced amino acid profile (Lu et al., 2022), however, it is important to add that this attribute varies greatly depending on parameters such as feedstock composition and larvae harvesting and processing. Marono et al. (2017) reported the level of lysine, methionine, methionine + cystine, isoleucine, valine, and threonine to be 4.1, 1.3, 1.4, 3.1, 5.0 and 2.32 %, respectively, on an as fed basis. These values were all higher than those reported for soybean meal (Makkar et al., 2014). However, soybean meal had higher tryptophan content (0.73 % as fed) than the BSFL (0.3 % as fed).

In addition to its high protein value, BSFL has a higher fat content compared to other plant and animal protein sources. The total lipid content of BSFL and pupae consists of roughly 19–40 % of unsaturated fatty acids and 58–72 % of saturated fatty acids (Makkar et al., 2014). However, its ω-3 fatty acids as well as other important fatty acids, such as lauric, stearic, linoleic, palmitic, and oleic acids vary greatly with feedstock used despite some scholars reporting higher levels of these fatty acids in BSFL (Surendra et al., 2016; Franco et al., 2021). Indeed, Li et al. (2017) found that the inclusion of BSFL in poultry and fish diets had a negative effect on the fatty acid profiles of the meat products, by decreasing polyunsaturated fats, while increasing saturated and monounsaturated fats. Nevertheless, this negative effect could be resolved by modifying the fatty acid contents of the BSFL's substrates, for example, by adding fish offal (Spranghers et al., 2017) and, possibly, seaweeds to food waste substrates as already discussed in this review. However, a recent study has shown that BSFL fat can still be used to replace soybean oil in broiler diets without compromising chicken production (Kierończyk et al., 2020).

Compared to the other insects that are currently used as ingredients in poultry diets, the BSFL has a higher concentration of calcium, copper, iron, manganese, phosphorus, and zinc (Makkar et al., 2014). However, it is worth noting that the nutritional composition of BSFL typically varies depending on the quality of feedstock (Lu et al., 2022), the developmental stage of the larvae (Lui et al., 2017), how the larvae was killed (Larouche et al., 2019), and the processing methods prior to incorporation into animal diets (Zulkifli et al., 2022). For example, when poultry feed, pig liver, pig manure, kitchen waste, fruits, vegetables, and rendered fish were used as substrates, mean larval size and weight were highest on kitchen waste, but the nutritive value of larvae was highest when fed liver and fish wastes (Nguyen et al., 2015).

7.2. Pharmaceutical value of black soldier fly larvae

In addition to its value as a nutrient source, BSFL also contains bioactive substances that may offer a wide range of health benefits to poultry. Wasko et al. (2016) reported that BSFL contains chitin, which is a primary component of the insect's skeleton. Chitin and chitin derivatives, such as chitosan and chito-oligosaccharides stimulate the innate immune system due to their fungistatic and immunoadjuvant properties (Józefiak et al., 2018; Lopez- Santamarina et al., 2020). In addition, chitin and its derivatives have demonstrated antibacterial, antifungal, and antiviral action against a variety of pathogenic microbes (Xing et al., 2015). Consequently, feeding diets containing chitosan and chito-oligosaccharides could reduce the need for prophylactic antibiotics in poultry production (Youssef et al., 2023; Ayman et al., 2022). However, of the use of BSFL chitin as an immune booster in poultry requires further research.

The BSFL fat is also high in essential fatty acids such as lauric acid, which accounts for 64% of total saturated fatty acids (de Souza Vilela et al., 2021). Lauric acid has been reported to possess anti-inflammatory properties and gut-modulating effects (Dörper et al., 2021). Indeed, incorporating BSFL into the diets of broiler chickens promoted intestinal health and reduced *E. coli* residues (Fortuoso et al., 2019). Furthermore, pathogenic microorganisms, like *Staphylococcus aureus*, cannot develop resistance to antimicrobial peptides present in BSF. This quality renders them valuable as antibiotic alternatives (Xia et al., 2021), given the challenge of antimicrobial resistance facing both animal and human health. There is evidence that antimicrobial peptides such as defensin-like peptides 2 and 4 (DLP2 and DLP4) reduced bacterial burden by more than 95 % in juvenile Jian carp organs such as the spleen and kidneys, lowered serum levels of proinflammatory cytokine, increased levels of anti-inflammatory cytokine, and repaired lung and spleen damage (Li et al., 2017). In addition, other antimicrobial peptides isolated from BSFL, such as sarcotoxin-1 and sarcotoxin-2a, have antibacterial activity against pathogenic microbes such as *S. aureus* and *Escherichia coli* (Elhag et al., 2017). Similarly, an *in vitro* study by Park et al. (2014) revealed that BSFL pharmaceuticals can inhibit the growth of several pathogenic microorganisms, including gram-positive *S. aureus*, methicillin-resistant *S. aureus*, and gram-negative *Pseudomonas aeruginosa*. These findings suggest that the inclusion of BSFL in poultry diets as a nutrient source could also prevent the development of infectious diseases and promote health and welfare of poultry. This would also reduce the overreliance on antibiotic growth promoters in intensive poultry production systems and contribute to socially sustainable future food systems.

8. Quality of products from poultry reared on black soldier fly larvae-containing diets

8.1. Meat quality

Picking and eating of live insects is part of the normal behaviour for birds raised extensively (Gasco et al., 2019), showing that palatability and intake of insect meals may not be a problem, all other things constant. Numerous studies have documented the successful incorporation of BSFL into chicken diets, indicating that its use as a protein source has positive results. Inclusion of BSFL in poultry diets has no negative effects on growth parameters, health status, or meat quality, and is credited with improved nutritional value (especially the amino acid content) of the meat in Japanese quail (*Coturnix coturnix japonica*) (Mat et al., 2021), Jumbo quail (Mbhele et al., 2019), broiler chickens (de Souza Vilela et al., 2021), and in Muscovy ducks (Gariglio et al., 2021).

The inclusion of BSFL oil to replace soybean oil had no negative impact on performance, carcass characteristics, and overall meat quality in broiler chickens (Schiavone et al., 2017a,b). The inclusion of BSFL fat up to 100 % enhanced the concentration of monounsaturated fatty acids (MUFA) but lowered PUFA in broiler chickens (Cullere et al., 2019). The low concentration of PUFA in BSFL-derived meat products is concerning because PUFA have health benefits for meat consumers. This suggests a need to fortify or enrich FW substrates with PUFA before use as BSFL substrate, but this requires further scientific exploration. This approach is important if the two-stage FW upcycling strategy is to produce poultry products of high quality that promotes human health. However, replacing soybean oil with BSFL fat had no effect on meat colour, odour, chewiness, juiciness, adhesiveness, lipid, protein, moisture, cholesterol, and thiobarbituric acid levels as well as on meat pH, thawing loss, and cooking loss in broiler chickens (Cullere et al., 2019). In contrast, Murawska et al. (2021) reported an increase in meat yellowness and pH values when soybean meal was replaced with BSFL at 50 and 75 % levels, respectively. The yellowness of the meat could be influenced by ommochrome pigmentation in BSFL's chitin (Ushakova et al., 2018), while the rise in meat pH could indicate poor muscle glycogen for the BSFL-group at slaughter. Schiavone et al. (2019) discovered that 10 % defatted BSFL meal supplementation increased meat redness and muscle protein content, whereas 15 % supplementation lowered meat yellowness, muscle moisture, and PUFA. The increase in meat redness could be attributed to melanin pigment from BSFL (Ushakova et al., 2018), while the increase in muscle protein could be due to the high compatibility of insect and meat proteins. The authors recommended modulation of the substrate to improve its fatty acid profile, which would warrant the production of poultry products with high levels of PUFA. This approach has already been discussed at length in this review. In another report, Moula et al. (2018) observed a 2.9 % increase in total meat fatty acids content of local poultry breeds when reared on diets containing BSFL compared to the control. This finding could be attributed to the high concentration of fatty acids (myristic, palmitic, palmitoleic, oleic, linoleic, linolenic, and stearic acids) in BSFL (Makkar et al., 2014). This is further corroborated by Gariglio et al. (2021), who showed that the use of BSFL in duck diets increased the concentration of lauric, myristic, and α-linolenic acids without altering the pH, colour, and saturated fatty acid content of the breast meat.

Apart from the mostly positive product nutrient composition outcomes in poultry fed BSFL-containing diets, there are concerns that consumers may not accept these poultry products. However, some recent surveys have shown that at least two-thirds of respondents approved the use of insect meal in animal feeds (Ribeiro et al., 2022; Sogari et al., 2022). Cultural differences are to be expected when it comes to consumer acceptance of poultry products derived from BSFL-fed birds. Moreover, it is essential to establish suitable policies and regulations to provide legitimacy to insect-based food waste bioconversion and the utilization of those insects as nutraceutical sources in animal diets. Consumer confidence and acceptance of poultry products is likely to increase once the industry is well-regulated. Overall, there is evidence that the use of BSFL as a feed ingredient promotes the production of high-quality poultry products that are rich in health-boosting bioactive substances for the benefit of the consumer.

8.2. Egg quality

When included as an alternative protein source in poultry feeds, insect meals have been shown to increase egg production, quality, and flavour (Thirumalaisamy et al., 2016; Star et al., 2020). The use of BSFL in large-scale commercial set ups encourages egg production and reduces feather pecking because insect meals are rich sources of minerals and amino acids. In a study of laying hens between the ages of 67 and 78 weeks, feather condition was better in hens fed live larvae compared to control hens fed a commercial diet (Star et al., 2020). According to Kawasaki et al. (2019), feeding laying hens with diets containing 100 g/kg BSFL resulted in thicker eggshells and heavier eggs compared to the control group, an outcome that was attributed to high calcium, methionine, lysine, and total protein content of the larvae (Lu et al., 2022). However, Heuel et al. (2021) found that the use of 150 g/kg defatted BSFL or 20 g/kg BSF fat in Lohmann Brown Classic hens had no effect on egg production and egg quality. The inconsistent results could be attributed to the different treatment levels, different rearing substrates, and different breed type used in the two studies. Although there are very few studies on the effect of BSFL in layer hens, it can be deduced from the nutritional profile of the BSFL that its high protein, amino acid, lipid, and mineral contents would promote the production of high-quality eggs that may provide much needed bioactive compounds with health-boosting and cholesterol-reducing effects. However, to achieve this, FW substrate enrichment prior to feeding the larvae may be necessary to ensure high-quality insect meals. In addition, harvesting the larvae before high levels of chitin have been deposited could enhance the nutritional value of BSFL in chickens.

9. Towards a two-stage upcycling strategy for food waste using black soldier fly larvae

9.1. .Elements and attributes

Fig. 2 provides an illustration of the two-stage FW upcycling strategy using black soldier fly larvae, which are then used as sustainable sources of essential nutrients and bioactive compounds in poultry diets. Using BSFL to convert biowaste into valuable products is a promising strategy for sustainable FW management and poultry production, supporting a circular global food system.

The BSFL-based upcycling approach can transform FW into nutrient-

Fig.. 2. An illustration of the food waste upcycling strategy using black soldier fly larvae, which are then used as sustainable sources of essential nutrients and bioactive compounds in poultry diets.

dense poultry products thus improving global food and nutrition security of the burgeoning human population. This strategy could also deliver poultry production systems that have lower environmental impacts, compete less for feed resources with humans, and are resilient to climate perturbations. Most FW streams contain large quantities of invaluable nutrients, such as carbohydrates, fibre, proteins, and lipids (Isibika et al., 2023), which should be recovered for re-use to resolve the FW problem and contribute towards sustainable food supply chains. Consequently, interest in the use of BSFL as an efficient FW converter and sustainable dietary protein source for food producing animals has grown immensely. The BSFL are currently one of the leading agents for the valorisation of FW (Ojha et al., 2020) because they have an aggressive appetite for organic wastes. Moreover, BSFL has been reported as an efficient bioconverter of FW (75 %), successfully recycling biowaste materials to produce about 800 g larvae biomass from 4 kg FW (Siddiqui et al., 2022).

Producing larvae from FW and using them as nutrient source for food animals, especially poultry, represents an important two-stage waste upcycling strategy with unequivocal benefits for food and nutrition security as well as environmental sustainability. In this strategy, amino acids, lipids, and energy are transferred from FW and concentrated into larval biomass before further upcycling into nutrient-dense poultry products. These animal products can play a crucial role in addressing the challenges of food and nutrition insecurity (Mlambo and Mapiye, 2015). This is especially important in low-income food-deficit countries where many people have inadequate access to dietary protein and energy while an even greater proportion suffers from micronutrient deficiency (Sutherland et al., 1999). The BSFL have the potential to replace a significant proportion of unsustainable plant and animal-based protein ingredients such as soybean meal and fish meal (Siddiqui et al., 2022).

9.2. *Constraints and possible solutions*

Upscaling this two-stage FW upcycling strategy using BSFL as a nutrient source in poultry diets offers numerous benefits, but it also presents several challenges that can be classified into technical and economic factors, consumer perceptions, sustainability concerns, and regulatory considerations. Technical constraints may include sophisticated infrastructure requirements (Jagtap et al., 2021), variable quality and quantity of FW feed stock streams (Isibika et al., 2023), expertise needed to maintain the health of insect colonies, scaling of larvae collection requiring automation, and management of waste (as well as odours) generated by larvae and spent FW feedstock. Large-scale BSFL production requires suitable facilities that provide controlled conditions for the incubation of larvae with FW feedstock. The quantity and quality of FW can vary, impacting on growth and nutrient content of BSFL. This could be resolved through the establishment of reliable FW feedstock supply chains to minimize the BSFL farm running under capacity or producing larvae of variable nutritional quality. Placing BSFL farms close to feedstock sources could mitigate the high cost of transporting

FW particularly high moisture streams. Using mixed FW streams can also improve quantity and quality reliability compared to mono-streams (Isibika et al., 2023). Blended FW streams have a better chance of providing a nutritionally balanced substrate for optimal BSFL growth and nutritional composition (Li et al., 2021; Singh et al., 2021). Viable large-scale cultivation of BSFL also requires effective integration and coordination of all the technical components and processes such as sourcing FW, managing environmental conditions, and automating larvae production and harvesting processes to ensure efficiency and scalability.

Economic constraints include the high initial capital investment required to set-up the specialized infrastructure, technology, and skilled labour for commercial BSFL production. In addition, operating costs arising from energy, labour, and maintenance costs can negatively affect economic viability of FW upcycling operations (Jagtap et al., 2021). The economic feasibility of the venture can also be limited by market acceptance of BSFL as a component of poultry diets as well as competitive pricing of other dietary protein sources such as soybeans. These constraints can be addressed through public-private partnerships (government agencies, research institutions, and private businesses) resulting in financial support, knowledge sharing, and infrastructure development for individual businesses. With regards to regulatory constraints, meeting regulatory standards may require costly compliance measures, providing a major stumbling block especially for new start-ups. However, an up-to-date regulatory framework can confer some legitimacy to BSFL-producing companies resulting in greater social acceptance. This is because negative consumer perceptions regarding the incorporation of insects into the diets of food animals also pose a significant hurdle, as the public may hold reservations related to safety and ethical concerns.

10. Regulatory and policy frameworks

Apart from the optimization processes already reviewed, the prospects of success for the two-stage FW upcycling strategy also rest on up-to-date and appropriate food and feed policies and regulations. Clear policies and regulations are likely to attract long-term investments into FW bioconversion using insects, thus accelerating the growth of this important industry. To a large extent, the European Union, USA, Canada, Australia, and most developed countries have existing standards that prescribe thorough safety assessments for insects used for food and feed (Lähteenmäki-Uutela et al., 2021) while only a few African countries that include Malawi, Tanzania, Kenya, Uganda (Niassy et al., 2022), and South Africa have done the same. Biologically sound policies and regulations are essential to ensure that the larvae from FW upcycling are environmentally sustainable and safe, especially when they are used as feed ingredients for poultry. Indeed, the conversion of FW through BSFL that is in-turn used as a feed ingredient for poultry can pose health risks to consumers through microbial, chemical, physical, and allergenic contaminants (Fowles and Nansen, 2020). Recent research indicates that many key insects employed in the bioconversion of food waste accumulate chemical contaminants at levels significantly lower than the maximum concentrations recommended by the European Commission and the World Health Organization (Purschke et al., 2017). In addition, Park et al. (2014) reported the secretion of antimicrobial peptides by BSF that can prevent the growth and transfer of pathogens that may be present in FW feedstock. In addition, thermal treatment of FW shows promising results against most pathogenic microorganisms (Chen et al., 2012). However, additional research is required to generate empirical data that can be used by regulatory agencies to safeguard product (insect meal and poultry products) safety, especially in developing countries. To attain legitimacy and social acceptance, enterprises engaged in insect-based FW bioconversion must ensure robust quality control practices at each stage of the upcycling process. This can be achieved through physicochemical and nutritional characterization of FW feedstock, BSFL produced, BSFL-based poultry diets, and poultry products. Specific policies and regulations are required to guide and monitor the FW-insect larvae-animal feed-poultry products value chain to ensure product safety and quality.

11. Conclusions and recommendations

While there is a broad political and scientific consensus on the importance of efficient reduction and upcycling strategies, establishing an effective framework for managing FW is an ongoing effort that is primarily focused on prevention. This review highlights the importance of optimizing FW streams for rapid BSFL growth, high biomass yields, and high nutrient content. Achieving this may require blending, fortification, or physical preprocessing of FW. However, it is crucial to recognize that this approach is one of many potential solutions to global FW issues and should not be viewed in isolation as a panacea. Instead, it represents a valuable option with substantial potential to contribute to a circular bioeconomy and sustainable food systems. Because of the abundance of FW as an inexpensive substrate, there is a high potential for scaling up the two-stage FW upcycling strategy. However, in most developing countries, supportive policies and regulatory frameworks for insect-based FW upcycling initiatives are lacking. Therefore, the call to action is for further research, policy development, and practical implementation of this cost-effective, efficient upcycling strategy, which can contribute to a robust FW management framework for sustainable future food systems.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve readability and language use in some parts of the paper. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Victor Mlambo: Conceptualization, Investigation, Methodology, Validation, Visualization, Supervision, Writing – original draft, Writing – review & editing. **Siphosethu Richard Dibakoane:** Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Thabang Mashiloane:** Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Ludzula Mukwevho:** Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Obiro Cuthbert Wokadala:** Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Caven Mguvane Mnisi:** Conceptualization, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

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

Data availability

This is a review paper

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