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Role of Black Soldier Fly Larvae in Sub-Saharan Africa Circular Bioeconomy

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The circular bioeconomy is an economic model that optimizes biological resources for maximum efficiency while minimizing waste through recycling, reuse and regeneration, in contrast to the traditional linear "take, make, dispose" approach (Ellen MacArthur Foundation, 2019; Muscat et al., 2021) in use for years. Expanding the circular bioeconomy can address concerns regarding waste management, food security and biodiversity loss, contributing to a more sustainable agricultural environment. However, organic waste management and livestock feed security remain critical challenges across much of Sub-Saharan Africa (SSA), worsened by inefficient waste disposal systems, high feed costs (related primarily to high import cost of feed ingredients like protein and energy), and environmental degradation.

The global human population is expected to approach 10 billion by the year 2050, possibly accompanied by a 70 percent increase in the demand for animal proteins (FAO, 2011). The trend has been for people to upgrade from vegetable-based to animal-based protein as their income increases (Hunter et al., 2017). However, insufficient protein consumption is Africa's primary source of malnutrition as animal-based protein is too expensive for most people to afford (Schönfeldt and Hall, 2012; Moughan, 2021). While the protein requirement is 0.7 g per kilogram body weight per day, the consumption in most SSA countries is under this threshold because most consumers cannot afford meat protein (Schönfeldt and Hall, 2012; OECD-FAO, 2021; Font-i-Furnols, 2023).

The low protein consumption level is due to the high cost of meat products resulting primarily from the major expense of animal feed protein ingredients, including soybean and fish meals, which hinders the profitability and growth of local meat production (Chia et al., 2019a; Hu et al., 2023). The livestock sector has much potential to play a major role in improving living standards and enhancing food security in developing countries (Armanda et al., 2019). For example, the commercial poultry industry offers animal protein production for human consumption (Butani et al., 2024) in a more cost-effective manner with a much shorter time interval than larger livestock species (cattle, swine, sheep, goats, etc.).

Recently, interest in insects has been growing on a global scale as a novel, cost-efficient and environmentally friendly technology to serve as an alternative protein source in animal feed (Suloma et al., 2014; Franco et al., 2021a, b; Raman et al., 2022; Weththasinghe et al., 2022; Romano et al., 2023). This is related to an intensified global emphasis on sustainable development and a circular bioeconomy, particularly in the areas of organic waste management, agriculture and food security (Wang et al., 2021; Koul et al., 2022; Manzoor et al., 2024). Black Soldier Fly (BSF), scientifically known as *Hermetia illucens* (Diptera: Stratiomyidae), has become the most promising insect candidate for large-scale industrial production. The BSF is a harmless insect with the potential to solve two of modern agriculture's growing problems, namely; 1) serving as a potential alternative protein source in the poultry feed industry and 2) environmentally efficient disposal of organic wastes, by-products and side streams (Taiwo and Otoo, 2013). In addition, the BSF exemplifies the circular bioeconomy by efficiently transforming organic waste into valuable protein resources (Bakker, 2020; van Huis et al., 2021). Yet, the emerging BSF industry remains in its infancy (Bukchin-Peles et al., 2025).

Insects used for feed can simultaneously improve waste management and enhance food security (Fadhila, 2020). Currently, BSF production systems utilize diverse feedstocks, including fruits, vegetables, animal byproducts and food waste (Surendra et al., 2020; Broeckx et al., 2021) to nourish larvae, which are then processed into products such as live or dried larvae, protein meal and oil for animal feed. In Africa, the present and modelled projections of production for black soldier fly larvae (BSFL) are estimated at 20,000 to 30,000 metric tons (Tanga and Kababu, 2023). This benefit of BSFL comes with potential ecological benefits as it can greatly decrease organic waste by about 85 percent and with a relatively high waste-to-biomass conversion rate of approximately 20 percent (Siddiqui et al., 2020; Mufungwe et al., 2025). Thus, BSFL technology presents an innovative, circular bioeconomy solution that simultaneously offers remarkable waste bioconversion and sustainable feed production (Anokye, 2025). Therefore, the BSFL has emerged as a promising alternative feed ingredient in broiler chicken diets, known for their high protein content and nutritional richness (Salahuddin et al., 2024).

In addition to high nutritional value, their environmental sustainability advantages are massive: they can efficiently treat large amounts of organic waste such as animal manure and food waste, significantly reducing environmental pollution and greenhouse gas (GHG) emissions (Boakye-Yiadom et al., 2022; Siddiqui et al., 2022). This dual benefit of resource conversion enables BSFL to hold a key position in modern agriculture and the circular economy (Su et al., 2025). Agriculture accounts for approximately 12 percent of global GHG emissions, equivalent to 5.87 gigatons (Gt) CO_2-eq (Gacuthi et al., 2026). (One gigaton is equal to one billion metric tons). Over 65 percent of agricultural emissions originate from livestock production, with enteric fermentation as the dominate source contributing approximately 2.8 Gt CO2-eq, followed by manure management and manure left on pastures (1.2 Gt CO_2-eq) (Symeon et al., 2025).

The practical applications of BSFL technology are gaining momentum worldwide, including SSA. In various countries, BSFL have been successfully integrated into circular bioeconomy models, where waste streams from food processing, agriculture and households are redirected toward insect farming to produce animal feed and biofertilizer (Anokye, 2025). For example, a BSFL project in Abidjan in the Ivory Coast addresses the city's daily production of 4,000 tons of food waste, reduces GHG emissions, supports local food security and creates sustainable livelihoods, particularly for women and youth (FAO, 2023). The BSFL efficiently process food waste, fruit and vegetable residues and farm waste, converting them into feed for chickens and fish and producing insect excrement used as organic fertilizer.

In Sydney, Australia, a project utilizes BSFL to process food waste from thousands of households, converting it into fertilizer and protein for animal feed (Anokye, 2025). In Kenya, Project Mila (which in Swahili means "tradition"), employs BSFL to address food waste and provide sustainable fish feed, reducing reliance on wild fish stocks and promoting environmental conservation (Ambole Okata, 2024). Similarly, farmers in Zimbabwe have adopted BSFL farming to produce affordable animal feed, thereby improving their livelihoods and contributing to environmental sustainability (Moyo, 2024).

Agricultural Sustainability and BSFL

The growing BSF recognition reinforces its strategic potential as a cornerstone for sustainable waste management and circular agricultural systems (Ungureanu and Vlădut, 2026). The potential of BSFL to process organic waste has gained more appreciation than other insect species (Siddiqui et al., 2022). Currently, BSF offers a solution to solve challenges related to global waste management, unemployment in urban areas and increased demand for sustainable animal feed (Dortmans et al., 2021). The benefits of using BSF in organic waste conversion from the perspective of waste managers include waste reduction in a short time, small carbon footprint, high conversion of feed substrate to body mass, being a non-disease vector species, as well as reducing pathogen and other pest populations while at the same time economically producing valuable materials that require low water and land usage compared to alternative protein sources (Siddiqui et al., 2022). Furthermore, Beskin et al. (2018) demonstrated the ability of BSFL to reduce the odorous compounds from poultry, swine and dairy manures by 87 percent or more. In addition, Bortolini et al. (2020) reported the benefits of BSF fits well in a circular economy due to the profitability of processing decaying organic matter into larval biomass and to the absence of remaining residue at the end of the process. Furthermore, the leftover frass (excreta of insects in the larval stage) as residue from the BSF system can be recycled back into the system to provide compost-like properties as an organic fertilizer and soil enhancer.

In addition, the valorization of agricultural residues through BSF bioconversion contributes to nutrient recycling and reduces the environmental impacts associated with residue disposal. Moreover, BSF-based systems can support rural bioeconomy development by enabling decentralized, farm-level waste treatment solutions (Fig. 1) that reduce reliance on centralized waste management infrastructure (Ungureanu and Vlădut, 2026).

Animal manure generated by farm-level livestock production systems represents a significant organic waste stream with considerable environmental implications, particularly regarding nutrient runoff, odor emissions and GHG emissions. However, BSFL have been shown to effectively reduce the volume and environmental impact of various manure types, including poultry, swine and cattle manure (Beskin et al., 2018). As a result, insect-mediated manure management has emerged as a promising alternative to conventional manure-to-resource and manure-to-energy conversion approaches (Cammack et al., 2021; Wu et al., 2024).

Figure 1. *Small, farm-scale BSFL colony containing organic household kitchen waste, animal manure and BSFL. Source: Tom Tabler*

In the context of developing countries, particularly in SSA, expanding livestock production is vital for food and nutrition security, income generation and poverty reduction (International Livestock Research Institute, 2013). However, growth of these sectors is constrained by several systemic issues–chief among them being the shortage and high cost of quality animal feed protein. The limited availability of affordable, high-quality feed hinders the productivity and profitability of smallholder farmers (Mnthambala et al., 2025). In Malawi, for example, feed costs remain a dominant barrier to the commercialization of animal agriculture and aquaculture, representing over 60 percent of production costs in fish and poultry farming and up to 80 percent in pig farming (El-Sayed et al., 2003; Jamu and Ayinla, 2003; Bulinda et al., 2023). There is an urgent need to identify locally available, cost-effective and sustainable feed alternatives that can enhance productivity without compromising environmental and public health. As a result, Mnthambala et al. (2025) concluded that BSFL feed is a viable and sustainable alternative, capable of reducing feed costs, supporting waste valorization and environmental sustainability and improving the resilience of animal production systems.

In Ghana, despite the dominance of large volumes of organic waste, its management remains highly inefficient, leading to significant environmental, health and economic consequences (Odonkor and Sallar, 2021; Vinti et al., 2023; Anokye et al., 2024a). The sources of organic waste in Ghana are diverse, including food waste, crop residues, livestock manure and agro-industrial byproducts such as cocoa husks, cassava peels and palm oil mill effluent (Addae et al., 2021). The predominant disposal methods for organic waste include landfilling, open dumping and incineration (Anokye, 2025). One of the key challenges is the absence of a well-structured policy on organic waste valorization. Economically, the failure to harness the potential of organic waste represents a missed opportunity for job creation and revenue generation (Ofei-Quartey et al., 2023: Anokye et al., 2024b). Organic waste can be converted into valuable products such as compost, biogas and animal feed, providing employment opportunities in waste collection, processing, and distribution. Countries like Kenya, South Africa and Nigeria have successfully implemented waste-to-wealth initiatives, where organic waste is processed into biofertilizers and sustainable feed alternatives (Anokye, 2025).

Sustainable feeding practices are essential for the poultry sector to achieve environmental and economic sustainability, especially in developing regions like SSA. High cost of poultry feeds, which make up 70 to 75 percent of the cost of production, is primarily influenced by the scarcity of critical protein ingredients like soybean and fish meals (Adeniji, 2007). These ingredients are favored in poultry diets due to their excellent palatability and high protein content. However, especially in developing countries, their reliance on imports and the associated high costs have prompted the consideration of alternative protein sources that could replace soybean and fish meals in poultry diets.

In recent years, the search for sustainable and environmentally friendly alternatives to soybean and fish meals as protein sources within the animal feed industry has focused on BSFL (Ee et al., 2022; Digiacomo, 2023; Dzepe et al., 2023; Sankara et al., 2023) more so than other insect species. Originating from South America, this species and its larvae have shown remarkable adaptability across a variety of climates, including temperate, subtropical and tropical landscapes.

Thriving best in temperatures of 77 F to 86 F (25 C to 30 C), BSFL can grow in a wide range of environmental conditions. Their unique adaptability, coupled with their preference for environments rich in decomposing organic matter, highlights their pivotal role in sustainable agriculture and waste management, suitable for numerous diverse geographical locations (Kaya et al., 2021; Lu et al., 2022; Pazmiño-Palomino et al., 2022). Fig. 2 provides an overview of the functional role of the BSF in nutrient recovery.

These larvae are nutritionally dense, with a rich composition of fats and proteins, making them an invaluable source of nutrients compared with conventional feed ingredients, suitable for a wide range of animals including poultry (Brede et al., 2018; Dabbou et al., 2018; Lee et al., 2018; Cullere et al., 2019; Kawasaki et al., 2019; Mbhele et al., 2019), fish (Xiao et al., 2018; Terova et al., 2019; Bruni et al., 2020; Fawole et al., 2020), and swine (Altmann et al., 2019; Biasato et al., 2019; Chia et al., 2019b). Their efficient waste conversion into usable biomass adheres to circular economy concepts, establishing BSFL as a trailblazer in advancing sustainable poultry farming operations (Salahuddin et al., 2024). The integration of BSF-based feed into the circular economy system is graphically depicted in Fig. 3, illustrating the flow of waste conversion, resource recovery, and nutrient recycling within sustainable agricultural systems (Tariq et al., 2025). The nutritional benefits of BSFL have much appeal in the animal feed industry, with a balanced amino acid profile and a high concentration of protein, energy and mono- and poly-unsaturated fatty acids (Mahmoud et al., 2022).

Figure 2. *BSF as a resource insect. Source: Tariq et al. (2025).*

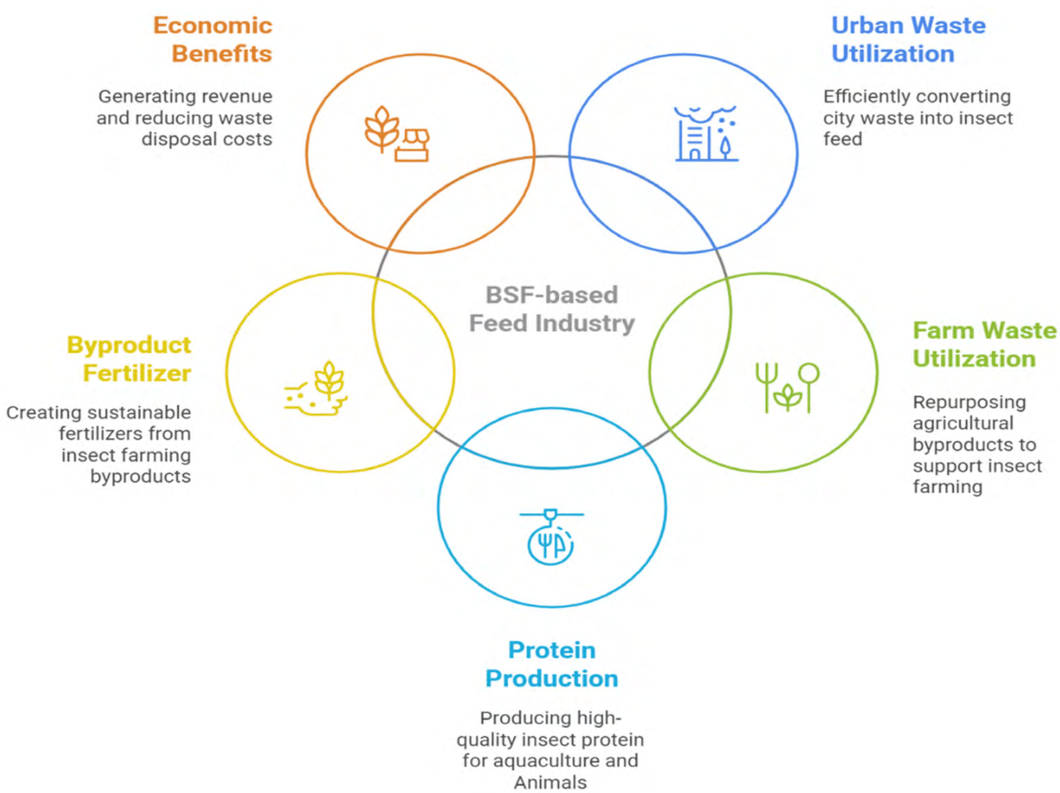

Figure 3. *BSF-based feed industry integration into the circular economy. Source: Tariq rt al. (2025).*

The effectiveness of BSFL as a feed ingredient largely depends on the nutritional composition, which includes high levels of protein, essential amino acids and lipids (Salahuddin et al., 2024). The larvae's age and developmental stage, as well as their diet, which can vary greatly based on the substrates they are fed (Rumpold and Schlūter, 2013; Barragan-Fonseca et al., 2017), affect their nutritional composition. How BSFL are processed, such as drying or pelleting, influences the digestibility and nutrient availability (Oonincx et al., 2015). In addition, the inclusion rate of BSFL in poultry diets warrants careful attention, as it can impact feed intake, nutrient absorption, and overall poultry performance (Biasato et al., 2016). Palatability is a significant factor, influencing poultry's acceptance of BSFL-based feeds because the texture and taste of the larvae can affect feed intake patterns, which in turn impacts nutrient utilization (Hwangbo et al., 2009).

Anti-nutritional factors present in BSFL, like chitin, require attention as well as they can impede nutrient absorption and digestion (De Marco et al., 2015). In addition, dietary requirements of laying hens differ from those of broilers, which could affect how nutrients from BSFL are utilized (Cutrignelli et al., 2018). Disease status and gut health of the birds are also critical, as they influence nutrient absorption and feed efficiency (Stanley et al., 2014). Environment (temperature and housing conditions) can play a role in feed intake, metabolic rate, and growth performance, thereby affecting the utilization of nutrients from BSFL (Bosch et al., 2019; de Silva and Hesselberg, 2020; Rummel et al., 2021; Pornsuwan et al., 2023). Understanding all the many ways these complex factors interact is vital for optimizing the use of BSFL in poultry diets.

Insect Interest Centers on BSFL

Scientific interest in insects as an alternative source of protein is no longer a novel idea and has grown considerably in recent years (Nachtigall et al., 2025). This growth in insect protein interest is driven by the rapidly growing human population, which has increased the demand for livestock and aquaculture products, requiring vast amounts of protein-based feeds (Namukonde et al., 2026). Hussein et al. (2017) estimated a 60 to 70 percent increase in consumption of animal products by 2050, which will increase the demand for animal feed ingredients such as grain (corn and soybeans), fish meal, meat and bone meal, etc. whose prices are already high (Hasimuna et al., 2019), especially in regions like SSA where often times import costs quickly drive up prices for protein ingredients in animal feed. In addition, availability of these ingredients may be limited in the future, given the estimated increase in demand for animal products and a changing climate. This opens the door for protein alternatives such as insect meals to compete with conventional protein sources like soybean and fish meals.

Like many other African countries, Zambia, for example, continues to grow its livestock sector and in recent years has experienced a boom in its fish and poultry farming activities (Songa and Mwiya, 2014). The growing demand for livestock feed raises significant environmental and food security concerns, primarily due to direct competition between humans and livestock for the same food sources (Hussein et al., 2017). These concerns are projected to intensify as climate change continues, further compromising water and land resources crucial for pastures and crop cultivation. However, insects can provide an excellent and sustainable protein source for animal feed (van Huis, 2013). They require fewer inputs to raise and offer highly digestible amino acid profiles (Nachtigall et al., 2025).

Moreover, insects are more environmentally friendly than conventional feed ingredients, such as soybean and fish meals, as they generate fewer GHG emissions and require significantly less land and water for production (Namukonde et al., 2026). Diverting organic waste away from landfills and open dumpsites will be critical to protecting the environment in the future. Organic waste is a major source of methane (CH_4) production, and CH_4 has approximately 27 to 30 times the global warming potential of CO_2 over 100 years (U.S. Environmental Protection Agency, 2025). The bioconversion capabilities of the BSF can effectively reduce organic waste decomposition and decrease GHG emissions from different organic waste substrates, with BSFL enhancing substrate aeration, assimilating carbon and nitrogen into biomass, and suppressing microbial pathways responsible for CH_4 and nitrous oxide production (Gacuthi et al., 2026).

Diverting organic waste into BSF production systems offers substantial climate benefits by reducing CH_4 emissions associated with uncontrolled decomposition. In rapidly urbanizing African cities where organic waste may constitute over 50 percent of municipal solid waste streams, BSF-based waste valorization represents a practical climate mitigation strategy while simultaneously generating agricultural inputs. Sub-Saharan Africa generates over 56 million metric tons of organic waste annually, much of which is mismanaged through open dumping and uncontrolled decomposition (Orhorhoro and Oghoghorie, 2019). The waste management challenge will become even greater as rapid urbanization and expanding livestock production in Kenya and other SSA countries are expected to markedly increase organic waste by 2030, emphasizing the need for sustainable waste valorization solutions (National Environment Management Authority, 2021). Global food waste amounted to 1.05 billion metric tons in 2022, and food loss and waste contribute 8 to 10 percent of global GHG emissions (Forbes et al., 2024). If just 1 percent of global food waste was diverted to BSF production, it could generate an estimated 332,000 metric tons of alternative protein annually while producing about 1 million metric tons of nutrient-rich organic fertilizer in the form of frass (Bukchin-Peles et al., 2025).

Poultry production continues to expand in developing countries, including Zambia and much of SSA. The increasing intensity of poultry production requires protein of high biological value (Hossain and Blair, 2007). Again, feed makes up about 70 to 75 percent of the total cost of poultry production, partially attributed to the high market price of conventional protein sources of both plant and animal origin (Abd-El-Hack et al., 2015). Soybean and fish meals discussed earlier are two conventional feedstuffs that increase the expense of feeds, in part, because humans also consume soybeans and fish (Kelemu et al., 2015). Alternative protein solutions are needed capable of substituting costly feed ingredients with less expensive, ecofriendly, high-quality protein ones (Goldansaz et al., 2017). Insects offer a promising potential poultry feed resource as they contain valuable nutrients that modulate animal microbiota and optimize animal health (Butani et al., 2024). In addition, the use of insects as poultry feed is not in direct competition with the human population as a food resource (Diener et al., 2011) at the same level as soybeans and fish, and consumers seem willing to accept food of animal origin produced with the use of insect materials as feed (Mancuso et al., 2016).

The BSF larvae are increasingly promoted as a sustainable ingredient in livestock diets for several reasons. First, BSFL are a powerful tool for biowaste recycling as the larvae feed on various biowaste materials (Liu et al., 2018; Surendra et al., 2020; Yildirim-Aksoy et al., 2020; Raman et al., 2022; Siddiqui et al., 2022; Weththasinghe et al., 2022; Romano et al., 2023; Scieuzo et al., 2023). Second, by feeding on a variety of biowaste materials, BSFL are climate-smart technology as they contribute to reducing GHG emissions generated by the decomposition of urban waste that otherwise might be dumped into unregulated landfills or open dumpsites (Liu et al., 2018; Surendra et al., 2020; Jung et al., 2022; Scieuzo et al., 2023). Third, BSFL are not only high in protein, but their lipid is useful in cosmetics and personal care products and biodiesel production (Franco et al., 2021a, b; Raman et al., 2022; Hu et al., 2023; Labella et al., 2024).

In addition, their frass is an essential source of soil nutrients (Tomberlin et al., 2009; Myers et al., 2014; Liu et al., 2017; Lomonaco et al., 2024). Finally, the remaining feedstock constitutes a very rich organic compost (Nyamuhirwa et al., 2025). Frass is nutrient-rich, containing 3.5 to 6 percent nitrogen (N), 1.5 to 3 percent phosphorus (P), and 1.2 to 2 percent potassium (K) (Wilson et al., 2025). It acts as a slow-release fertilizer, reducing N volatilization by up to 40 percent and minimizing leaching (Jenkins, et al., 2023). Frass enhances soil microbial activity and respiration up to 25 times, improving soil fertility and structure (Praeg and Klammsteiner, 2024). Studies have shown that frass increases crop yields by up to 30 percent as well as supporting nutrient cycling, aided by nitrogen-fixing bacteria (Agustiyani et al., 2021; Terfa, 2021). Frass also stabilizes organic carbon, contributing to long-term carbon sequestration (Boudabbous et al., 2023). As a result, the combined production of feed and fertilizer improves the overall economics and sustainability of BSF enterprises, further promoting circular bioeconomy principles.

The interest and use of novel feed ingredients such as BSFL continues to grow globally (Ouko et al., 2022; Koech et al., 2023) and is considered a viable alternative to traditional feed ingredients (i.e. soybean and fish meals), especially in the framework of sustainability and a circular economy (Ouko et al., 2022; Mufungwe et al., 2025). However, the increased use of BSFL is relatively slow in some parts of SSA including Zambia, which could benefit from its potential to diversify commercial feed formulation (Hussein et al., 2017; Siamabele, 2019; Koech et al., 2023; Nguezet et al., 2024) and ultimately boost revenues accrued from the livestock industry (Roy et al., 2024). In SSA, the lack of BSF knowledge among individuals serves as a significant obstacle to accepting BSFL as a feed ingredient (Koech et al., 2023). The slow acceptance rate is likely a result of multiple factors that relate to consumer needs and pertain to individual and social factors (Kauppi et al., 2019; Koech et al., 2023), product suitability (Kauppi et al., 2019; Selaledi et al., 2021, Mufungwe et al., 2025) and adoption strategies (Kauppi et al., 2019).

However, an increase in global poultry production numbers calls for the improvement in poultry manure management methods. On poultry farms, the accumulation of manure could be reduced by almost 60 percent through the feeding of BSFL (Siddiqui et al., 2022). Furthermore, while the larvae can reduce the amount of chicken manure up to 56 percent and convert it into biomass high in protein and fat that may serve as animal feed, it could also increase the net revenue of a layer house by about $25,000 yearly (Newton et al., 2005). Similar research has indicated an average of 52 percent substrate reduction and 28 percent bioconversion ratio (both on a dry matter basis) on food waste during a 14-day experiment (Ermolaev et al., 2019).

BSF Life Cycle

A major advantage of using the BSF as an alternative protein source is the short lifecycle, lasting 45 days with four stages: egg (4 days), larva (with five instars) (13-18 days), prepupa (7-14 days) and adult (5-9 days) (Fig. 4). A new life cycle starts from an egg, which also marks the end of the previous life stage as the female dies after laying eggs (Dortmans et al., 2017). A female lays 500 to 900 eggs in tiny, dry and well-sheltered cavities close to a food source, preferably decomposing organic matter. This strategy is to protect the eggs from predators and prevent dehydration from direct sunlight and to increase the chances of survival of the larvae upon hatching (Dorrmans et al., 2017).

After hatching, the larvae are voracious eaters that allow them to store enough fats and proteins to aid in the process of pupation, fly emergence, mating and oviposition. Larval development is in five instars and takes a period of 14 to 16 days under optimal conditions (Shumo et al., 2019).

As mentioned earlier, optimal temperature is 77 F to 86 F (25 C to 30 C). Temperatures above 86 F (30 C) trigger the larvae to move away from the substrate in search of cooler areas while temperatures below 75 F (24 C) reduce the metabolic activity of the insect slowing the growth rate (Holmes et al., 2012; Dortmans et al., 2017). The optimum relative humidity for growth of the BSFL ranges between 60 to 70 percent, while the recommended substrate moisture level ranges between 52 and 70 percent (Holmes et al., 2012). However, BSFL can prolong their life cycle during unfavorable conditions (Shumo et al., 2019) if necessary.

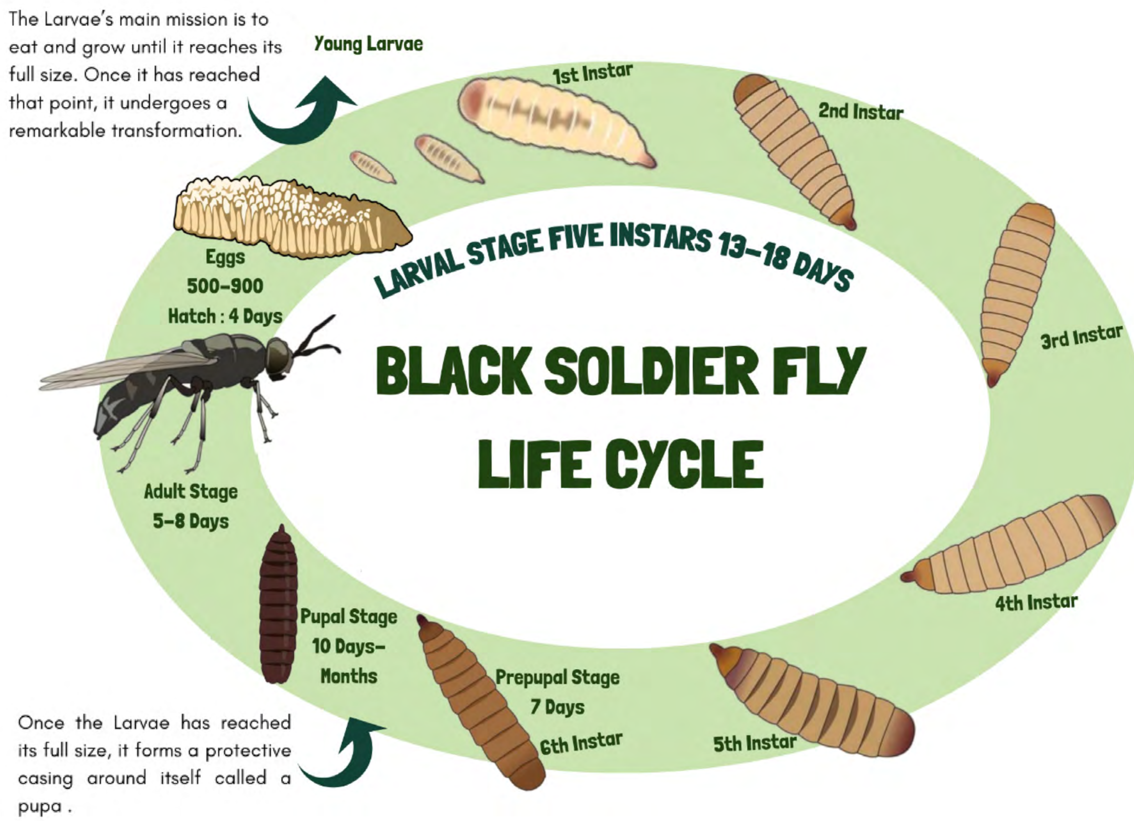

Figure. 4. *Black soldier fly life cycle with each developmental stage. Source: Tariq et al. (2025).*

The larval stage is followed by a pupae stage symbolized by the replacement of the larval mouth parts with a hook-shaped structure and a color change from cream to dark brown/charcoal grey. The pupa uses its hook-shaped structure to move out and away from the substrate into a shaded and protected environment safe from predators (Zurbrūgg et al., 2018). The pupation stage takes between two to three weeks and is marked by the transformation of the pupa into a fly. The emergent fly does not feed and is only dependent on water for development along the life cycle (Zurbrūgg et al., 2018). As an adult, the fly searches for a mate, copulates and the female lays eggs in well-shaded dark crevices near substrates (Lee et al., 2020). While light intensity affects both mating and egg fertilization, it has been suggested that light spectral composition plays a more important role in fertilization than light intensity (Butani et al., 2024). Light-emitting diodes producing wavelengths in the UV, blue, and green ranges have proved to increase the proportion of fertilized eggs (Oonincx et al., 2015).

BSF and the Circular Bioeconomy in Africa

We have focused much attention on the ability of BSFL to serve as a feed ingredient, but the BSF potential goes far beyond an alternative protein source. In the urban markets of Nairobi and Kiambu in Kenya, and Soroti in Uganda, up to 40 percent of fruits and vegetables are wasted, increasing to 60 percent during the rainy season (Climate and Clean Air Coalition (CCAC), 2024). Food waste, defined as the food that is removed from the human food supply chain from households and the retail and food service sectors, is one of the great paradoxes of our time. Average global per capita food loss and waste have increased 44 percent between 1961 and 2011 (Porter et al., 2016).

In 2017, there was approximately 1.9 Gt of food waste, which accounted for 29 percent of all total primary food production (Guo et al., 2020). The Food and Agriculture Organization (FAO) (2019) indicated that approximately 30 percent of the world's agricultural land was used to produce food that was either lost or wasted. Food loss happens in the upstream stages of the supply (farms, aggregation centers, during transportation, and at the wholesale and retail markets), while food waste occurs in the downstream stages, which involves the consumption levels (restaurants and households) (FAO, 2019). Food waste is a predominant phenomenon in high income countries, whereas food loss primarily occurs in developing countries, caused by many factors (Aragie et al., 2018).

These include but are not limited to highly fragmented smallholder production, poor handling practices, low levels of knowledge on proper handling, limited financing options to facilitate technology adoption, poor infrastructure, poor market forecasting brought about by misinformation by middlemen, low industrial processing capabilities, and low exports, among others (Ridolfi et al., 2018; Flanagan et al., 2019). As a result, the quantity and caloric value of food lost in SSA has been reported to be about 15.9 percent and 17.2 percent, respectively (Owino et al., 2025). Across SSA, more than 174 million tons of organic waste are produced annually (CCAC, 2024). This inefficient waste management not only contributes to environmental degradation and global warming through GHG emissions but also impacts on human health due to unpleasant odors and potential contaminations at disposal sites, resulting in economic losses across the agricultural value chain.

In addition, the extensive use of inorganic fertilizers in these regions compromises soil fertility by harming organic matter, increasing acidity, and reducing microbial diversity, which in turn lowers air and water quality and diminishes crop yields (CCAC, 2024). A CCAC-funded project, Waste to Wealth: Using Innovative Gender-Responsive Business Models to Turn Organic Market Waste into Organic Fertilizer and Animal Feeds (WaWe), demonstrates that the BSF is an integrated bioeconomy technology capable of transforming organic waste streams into multiple products that include:

- BSF larvae meal for poultry and aquaculture feed.
- BSF oil for biodiesel and industrial applications.
- BSF frass for organic fertilizer.
- Reduced methane emissions from unmanaged organic waste.
- Youth and women-led enterprise opportunities.
- Improved urban sanitation and waste management.

The current attention on the BSF comes not only from its ability to create value from waste but also in addressing environmental, economic, and social challenges simultaneously. The WaWe project provides an excellent case study of this integrated approach:

Market waste → BSFL production → animal feed + organic fertilizer → increased agricultural productivity → reduced waste disposal costs → employment creation.

The Waste-to-Wealth initiative implemented by partners including the United Nations Environment Programme (UNEP), Stockholm Environment Institute-Africa Centre (SEI), and local institutions in Kenya demonstrates how organic market waste can be transformed into valuable agricultural inputs through BSF technologies. Through gender-responsive business models, the project supports women and youth enterprises that convert vegetable and fruit market residues into insect protein and organic fertilizers, simultaneously addressing urban waste management, climate mitigation, and livelihood generation, especially from gender and youth dimensions, because the WaWe project specifically promotes:

- Women-owned enterprises
- Youth-led waste collection/bioconversion businesses
- Green jobs, and
- Informal sector integration.

Such initiatives illustrate the practical potential of BSF systems within emerging African circular bioeconomies. Beyond technical performance, BSF enterprises present significant opportunities for gender-inclusive entrepreneurship. In many African countries, women and youth dominate waste collection, market trading, and small livestock enterprises like poultry and small ruminants. Impactful BSF technologies provide pathways for upgrading these activities into profitable circular bioeconomy enterprises while enhancing environmental sustainability, aligning strongly with several of the 17 United Nations Sustainable Development Goals (SDGs) including, 5 (Gender Equality), 8 (Decent Work and Economic Growth), 12 (Responsible Consumption and Production), and 13 (Climate Action).

The BSF has an interesting history where, at one time, it was considered a pest due to its ability to colonize organic waste and manure, while in today's society, for the very same reason, this feature has made it the "crown jewel" of the insects-as-feed industry and is a key asset in its transition for use as a valuable tool used as part of a circular economy (Tomberlin and van Huis, 2020). The realization of its potential in recycling organic matter and use as a feed source started only about 25 to 35 years ago. Even more amazing is the fact that the worldwide focus of academia and private enterprise regarding BSF technology started only about 10 years ago.

As indicated earlier, the BSF contributes to circular economy sustainability by efficiently converting organic waste into valuable resources like high-protein biomass and nutrient-rich frass, which can be used as animal feed and organic fertilizer, respectively (Lalander et al., 2015; Liu et al., 2019). Integrating BSF into waste management systems reduces reliance on synthetic inputs and lowers environmental impacts, aligning with sustainability goals and minimizing CO_2 emissions (Barragan-Fonseca et al., 2017; Bessa and Hoffman, 2020). Recent research indicates that the BSF uses waste reduction and resource recovery to make animal feed, lipids, chitin, and fertilizer (frass), suggesting a circular economy (Tariq et al., 2025). A circular bioeconomy may be promoted by turning low-value byproducts into protein meal and oil. Economic opportunities in the BSF industry are rapidly developing, providing a sustainable alternative to traditional livestock feed, thus supporting food security and resource conservation (Odongo et al., 2024). As a result, BSF integration into circular economy frameworks effectively recycles organic waste into valuable biomass.

The BSF has been used in food waste treatment and energy generation and shows potential not only as animal feed but also in biofuel production (Mutafela, 2015; Kim et al., 2021). Research indicates that the BSF can convert mushroom substrates, wet distiller's grains, kitchen waste, manure, and biosolids into protein- and fat-rich biomass (Tariq et al., 2025). In fact, 100 percent wet distiller's grain is suitable for the growth of BSFL and can promote the humidification of the substrate during the treatment process, increasing the content of total Kjeldahl N, total organic carbon, total P, and total K in the residues (Wei et al., 2024). In addition, insect synthetic biology could be used to valorize organic waste by utilizing insects that are already adept at processing organic wastes as a platform for biomanufacturing and bioremediation (Tepper et al., 2024).

Insect Biomanufacturing

Biomanufacturing is the use of biological systems and their cellular machinery to generate valuable biomolecules with utility in industries such as agriculture, food, pharmaceutical, material and energy (Zhang et al., 2017). Microbial fermentation systems and cell lines have been particularly invaluable to commercial biomanufacturing due to the relatively simple rearing conditions, fast growth rates, ease of storage, established genetic manipulation methodologies and diverse metabolic potentials (Tepper et al., 2024).

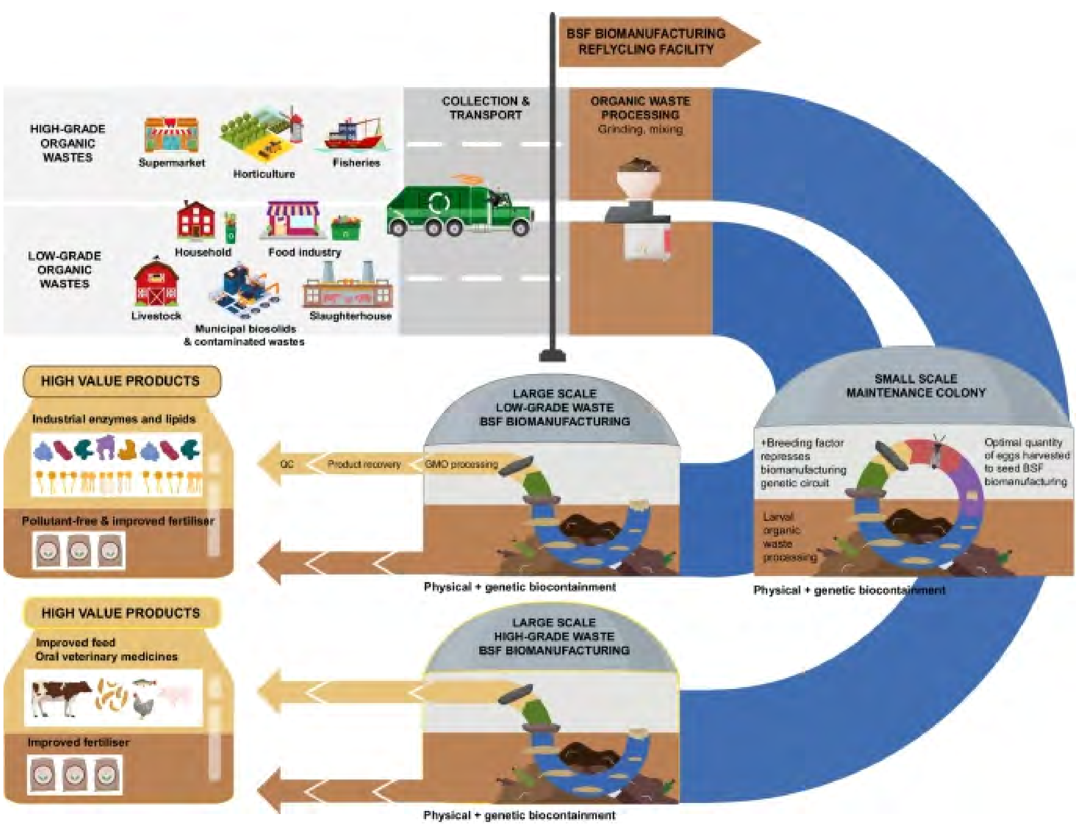

Figure 5. *Black soldier fly biomanufacturing facilities could valorize a wide variety of organic wastes into high-value products. Source: Tepper et al. (2024).*

Insect biomanufacturing is far from a new field of study. Beekeeping for honey, beeswax and pollination has existed since the dawn of agriculture, with evidence of humans using beeswax found across Neolithic Europe, the Near East and North Africa (Roddet-Salque et al., 2015). Silk production from the cocoon of the silkworm (*Bombyx mori*) originated in China in the third millennium BC, and silk remains a high-value product to this day. Utilizing BSF to support a circular bioeconomy involves considering both waste streams and products (frass). Waste streams may be broadly divided into two categories: 1) those suitable to produce food/feed and 2) those that are not. The former high-grade wastes include horticultural, food manufacturing, fisheries and pre-consumer food waste (Lähteenmäki-Uutela et al., 2021). The latter includes low-grade wastes such as restaurant and post-consumer household organic waste, processing/slaughterhouse waste, livestock manure, municipal biosolids and organic wastes contaminated with hazardous compounds.

A major limitation of using BSF to generate animal feeds from waste are regulations which preclude using low-grade organic wastes to rear BSFL for feed (Lähteenmäki-Uutela et al., 2021). However, BSF could valorize both high- and low-grade waste by utilizing BSFL as a platform for biomanufacturing and bioremediation (Fig. 5) (Tepper et al, 2024). Black soldier fly larvae could convert greater varieties of low-grade organic wastes into insect biomass utilized to biomanufacture a large variety of high-value biomolecules such as industrial enzymes and lipids that are not subject to food/feed regulations. The previously mentioned frass generated by the BSFL could serve as an enhanced fertilizer further supporting a circular bioeconomy.

Summary

Despite the clear benefits of BSFL as an animal feed, its adoption across much of SSA may be hindered by existing perceptions and attitudes among livestock smallholders and consumers. Adoption is currently low across SSA, and little is known about the determinants of livestock farmers' decision to adopt BSFL. Adoption of BSFL will depend on successful awareness creation. Other important constraints that must be leveraged include targeting educated farmers and group members, credit organizations, Extension services, and income diversification opportunities to support smallholders' decisions to adopt new products aimed at sustainable livestock farming. Understanding how BSFL is perceived (cognitive appraisal) and the subsequent reactions (attitudes) towards it is critical, as these factors can significantly influence its acceptance as animal feed and, consequently, the consumption of livestock products reared using it. However, converting low-value inputs that cannot be utilized directly for livestock and aquaculture diets into high-value feed ingredients like BSFL protein meal or oil which have application in many animal feed sectors allows these technologies to stand out from alternative waste management approaches and support a more circular bioeconomy across SSA.

We have only scratched the surface regarding the potential of the BSF. Certainly, the potential of BSFL as an alternative protein source and feed ingredient should be expanded, as should the use of frass as a nutrient-rich organic fertilizer. However, there are numerous other areas related to regenerative and climate-smart agriculture where BSF can play a key role that are yet to be investigated on a large scale across SSA. These areas offer untapped possibilities that deserve at least the same level of attention being given to BSFL as an alternative protein source and include 1) nutrient cycling, 2) reduced external inputs, 3) waste valorization, 4) local feed production, 5) reduced feed import dependence and 6) increased resilience of smallholder systems.

Additional policy recommendations for Africa include:

1. Recognition of insect protein within national feed regulations.
2. Development of BSF quality standards.
3. Support for organic waste segregation at the source.
4. Public-private partnerships for municipal organic waste valorization.
5. Integration of BSF into national bioeconomy strategies
6. Inclusion of BSF technologies in climate adaptation and mitigation programs.

This is particularly relevant as Kenya develops its National Bioeconomy Strategy and several other African countries seek circular economy solutions.

The BSF offers a natural and sustainable solution to massive world challenges like managing waste, reducing pollution, improving food security and transitioning to a circular bioeconomy. The BSF larvae can convert almost any type of organic waste, such as food waste and farm manure, into useful products, such as high-protein animal feed, oils for biodiesel and natural fertilizers. This bioconversion process has the potential to reduce waste, cut GHG emissions, improve soil health, and lock away carbon for the long term. Black soldier fly larvae are remarkably adaptable, thriving in various climates and conditions in both cities and rural areas. There are challenges to address such as public perception, unclear regulations, and cultural attitudes toward insect-based solutions. However, as BSF farming becomes more efficient, scalable, and affordable for industries and communities, BSFL systems can help replace traditional animal feeds and synthetic fertilizers, promoting ecofriendly practices and playing a major role in the circular bioeconomy across SSA.

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