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AFRICAN JOURNAL OF SCIENCE, TECHNOLOGY AND SOCIAL SCIENCES

AJSTSS
AFRICAN JOURNAL OF SCIENCE, TECHNOLOGY AND SOCIAL SCIENCES

Journal website: https://journals.must.ac.ke

MERU UNIVERSITY OF SCIENCE AND TECHNOLOGY

A Publication of Meru University of Science and Technology

Resource recovery from organic wastes using Black Soldier Fly Larvae

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ARTICLE INFO

KEY WORDS

Environmental Management

Nutrient Recovery

Waste Reduction

ABSTRACT

Solid waste management is a cross-cutting issue impacting many aspects of the environment, society and economic development. Cities of low- and middle-income countries are currently facing severe challenges in management of the increasing amount of solid waste produced, particularly the organic waste fraction. This review presents information in literature about the utilization of Black soldier fly (BSF) in managing organic waste. It summarizes the approaches in organic waste management, use of BSF in organic waste management, life cycle and growth conditions of BSF and the benefits of utilizing BSF for resource recovery. Organic waste treatment using BSF is an emerging waste management technology with minimal global warming potential. The BSF larvae helps in carbon sequestration and is a protein source which can help alleviate the raising global demand for animal feed. The BSF larval model provides for nutrient recycling, waste reduction and value addition significantly contributing to economic viability, competitiveness and strategic development in environmental management and agriculture.

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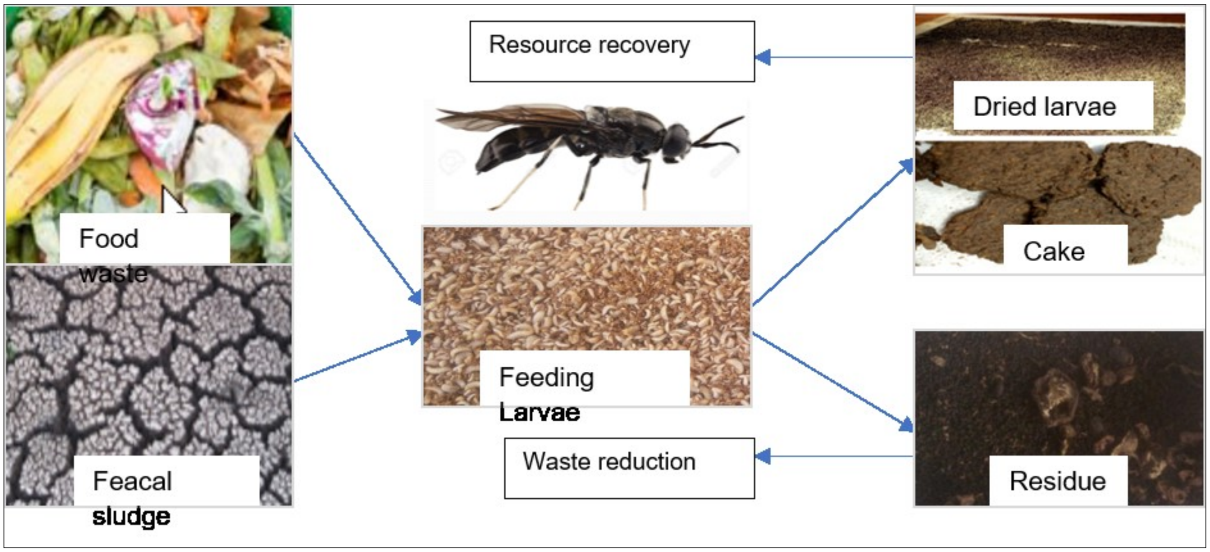
https://doi.org/10.58506/ajstss.v1i2.14

AFRICAN JOURNAL OF SCIENCE, TECHNOLOGY AND SOCIAL SCIENCES ISSN :2958-0560



Introduction

Rapid urbanization and change in human consumption patterns has resulted to new challenges in solid waste management (SWM) for decision makers and municipalities (Ezugwu, 2015): particularly in public health and environmental sectors in developing countries. The situation is severe in Africa, especially in large urban centers. Expansion of commercial and industrial sectors in Kenya for instance, has resulted to increased urban migration, improved standard of living and technological advancement which has contributed to increased waste generation (Njoroge, Kimani & Ndunge, 2014) that has impacted many aspects of the environment, society and the economy. The main objectives of SWM are to address health, environmental, land-use, resource, aesthetic, and economic concerns associated with improper disposal of waste (Ezugwu, 2015).

Management of solid waste in developing and under developed countries is characterized by informal solid waste separation, well-established recycling and resource recovery sector for inorganic and potentially recyclable material such as glass, metal and plastics which creates job opportunities and income generation. A study in Nairobi by Kasozi & Blottnitz (2010) concluded that overall solid waste composition that could enhance downstream material recovery and value generation includes 50.9 % organic materials, 37.7% potentially recyclable materials and 11.4% residual materials. However, the organic waste fraction is looked upon as waste without market value and waste recycling is still in the embryonic stage (Dortmans, Diener, Verstappen & Zurbrugg, 2017) in developing countries. Moreover, organic waste management is challenging due to its rapid degradability and bulky nature (Surendra, Olivier, Tomberlin, Jha & Khanal, 2016). Treatment of organic waste in these countries would significantly improve the whole waste management system since it accounts for 50-80% of the municipal solid waste generated (Lohri, Diener, Zabaleta, Mertenat & Zurbrugg, 2017). Different approaches are being used currently in organic waste management. However, improper solid waste management planning, lack of technical expertise and equipment for collection, transportation, treatment and disposal of solid waste, insufficient financial resources and public attitude have made the situation exasperating (Srivastava, Ismael, Singh & Singh, 2014).

Due to lack of alternatives, biowaste is often dumped arbitrary in landfills or on uncontrolled dump sites, where the material decomposes in large heaps under anaerobic conditions resulting to adverse impacts on the environment such as water pollution, providing breeding places for pathogen transmitting insects and greenhouse gas emissions among others (Wilson, 2015). In addition, poor organic waste management practices waste nutrients and energy that could be used to meet the increasing resource demands globally (Popa & Green, 2012). Collection and nutrient recovery from municipal organic waste can significantly mitigate these problems. Besides, natural resources are being depleted at the same time. Thus, establishment of a circular nutrient metabolism requires action along the entire food chain from food production and processing to consumption and waste management (Van Huis, 2013). This requires a paradigm shift toward a circular economy aiming to close the loop which is achievable through biowaste valorization (Lohri et al., 2017) which is an important feature of sustainable development. Addressing this challenges would also significantly contribute towards the achievement of the Sustainable

Development Goals (SDGs) related and not limited to: health, food and resource security, climate change, poverty alleviation, responsible consumption and production (Wilson, 2015). As a result, the end-of-pipe waste management practices would be alleviated.

Approaches in Organic Waste Management

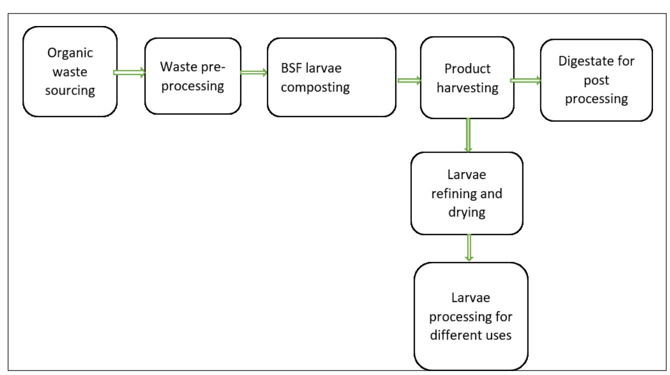
Currently, the main approaches in organic waste management include incineration, land fill, composting and waste stabilization/treatment through anaerobic digestion (Surendra et al., 2016). The inadequacy of the biowaste management approaches results in devastating environmental and anthropogenic impacts. For instance, landfills act as a repository for biogenic carbon through biodegradation to methane which can be potentially recovered for use as energy. However, landfills are reported as the second-largest source of anthropogenic CH4 emissions (US EPA, 2008) due to CH4 gas that is not collected,. In addition, the disposed organic waste in landfills is normally broken down and decomposed by microorganisms to form heavily polluted leachate that contaminates the groundwater (Eco-cycle, 2011). On the other hand, the incineration of biodegradable solid wastes with a high moisture content lead to the release of dioxins (Katami et al., 2004) which are highly toxic and persistent pollutants that pose a threat to humans and the environment (Paritosh et al., 2017). Moreover, incineration minimizes the economic value of the biowaste by preventing the recovery of nutrients from the incinerated organic waste.

Anaerobic digestion approach is an ecofriendly and promising solutions for food wastes management, energy, and nutrient production, which can contribute to world's ever-increasing energy requirements (Paritosh et al., 2017). Ferreira et al. (2018) reported that composting is an alternative for recycling biodegradable organic waste and transforming it into an organic fertilizer, thus minimizing the amount of waste sent to landfills. However, its low economic revenue limits the interest of the composting process. These current policies for organic waste management are greatly restricted to collection, transportation, treatment and disposal, thus lacking large scale valorization of organic waste for inherent nutrient and economic value determination (Singh & Kumari, 2019). Therefore, the application of Hermetia illucens larvae is an emerging green technology in organic waste management.

Use of BSF in Managing Organic Waste

The need for better resource recovery has spurred efforts towards more comprehensive recycling of nutrients contained in organic waste for animal feed formulation, soil conditioning, solid fuel and feedstock for production of biogas. Bioconversion by insects is one of the most innovative technologies for waste management (Caligiani et al., 2018) since they increase the productivity and efficiency of the food chain (Van Huis, 2013). Naturally, most insects feed on organic wastes, convert biomass nutrients into their own body biomass which results in significant reductions in the waste quantity while simultaneously limiting the amount of organic material disposed in landfills. Caligiani et al. (2018) highlighted that the use of the larvae of Black Soldier Fly Larvae (BSFL), botanically called Hermetia illucens (L.), is a prospective solution for organic waste management. Moreover, Bosch et al. (2019) proposed that BSFL have a crucial role to play in the framework of the circular economy by recycling resources that have zero-value or that do not find a reallocation in the food chain. BSFL treatment technology integrates organic waste composting, nutrient recovery and income generation. BSF are harmless insects that can provide promising solutions to the disposal of large quantities of eliminated organic waste as illustrated in Figure 1. A study by Nguyen, Tomberlin & Vanlaerhoven (2015) suggested BSF as an effective insect for converting many types of organic wastes of minimal value such as waste plant tissues, food waste, animal manure and animal offal into valuable insect biomass which is a useful ingredient for animal feed. Lalander, Diener, Zurbrügg & Vinnerås (2019) found out that BSFL are versatile in their feed preferences and can treat a variety of organic waste streams given that Nitrogen (N) and Total Volatile Solids (TVS) content are high to support the larval growth.

Figure 1: *Simplified Flowchart of Organic Waste Treatment Using BSF Larvae*



Treatment of organic wastes improves environmental and public health through pathogen reduction, stabilization of organic matter and nutrients, and the safe end use or disposal of treated end products. BSFL organic waste treatment facilities have low installation and maintenance costs and need no power supply. Furthermore, creating additional value chains and generating a surplus income through the sale of harvested prepupa can strengthen the economic resilience of farmers or small entrepreneurs to natural hazards or market fluctuations (Diener et al., 2011). It enables income generation for small entrepreneurs with little investment. Thus, BSF's capacity to reduce huge quantities of waste presents an opportunity for establishment of a circular, rather than linear, nutrient metabolism and food economy (Nguyen et al., 2015).

Life Cycle and Growth Conditions

BSF can be maintained in a colony and there is an increasing global interest in the mass production of the insect. BSF is a native detritivorous insect of the tropical, subtropical and warm temperate zones of America (Tomberlin, sheppard & Joyce, 2002). However, it is now found in different parts of the world especially in the tropical and warmer temperate regions. Diener et al. (2011) reported that BSF are now found between 45oN and 40oS, showing the vast range in which, they occur. In addition, they are tolerable to temperature extremes by a wide range throughout their life cycle, except during ovipositing.

BSF undergo five stages in a complete life cycle namely: egg, larval, prepupal, pupal and adult stages (Banks et al., 2014). The larval and pupa stages of the BSF are the longest part of their life cycle whereas their egg and adult stages are relatively shorter (Popa & Green, 2012). The beneficial characteristic of adult BSF is that they do not have functional mouth parts, thus adults do not feed but depend on the fat stored during their larval stage (Tomberlin et al., 2002). Furthermore, adult BSF are not pests since they do not enter into buildings and have a relatively short life span (Tomberlin et al., 2002). Adults BSF are able to mate within two days of emerging from the pupa (Joyce, Sheppard, Kiser, Tomberlin & Sumner, 2009) since they only live for approximately 5-8 days in which they should mate and lay eggs. When mating time comes, they look for secluded bushes where the males choose a partner to mate with, which is achieved through lekking. Lekking is a mating behaviour where males of a species congregate in certain areas and 'call' to the females of the species (Karagodin, Yurina, Bastrakov & Ushakova, 2017).This takes place at a distance from the waste because the female should lay her eggs near a food source where her offspring will easily feed. Each female has the ability to lay clusters of between 500 and 900 eggs (Banks et al., 2014). Female adult lays her eggs in cracks and crevices which are slightly separated from the food source. Within 102 to 105 hours, laid eggs hatch (Tomberlin et al., 2002) but there's need for optimum environmental conditions for this to be achieved.

The larval stage succeeds the egg stage. Hatched larvae craw into the food source (Banks, Gibson & Cameron, 2014b) which justifies the importance of the female adults to lay their eggs near a food source. The BSF larvae have a black eye spot and translucent bodies. Banks et al. (2014) highlights that the larvae have a greatly unique composition of the gut microbiota which enables them to handle a wide range of feeds such as animal manure, human and animal cadavers, palm kernel meal, municipal organic waste, decaying vegetables, fresh fecal waste and pit latrine fecal sludge. The larval stage is the most crucial stage of BSF concerning waste management since the fly accumulates its fat body only during the larval stage, while adult nourishment is less vital and mostly influences longevity (Tomberlin et al., 2002).The larvae are easy to keep and able to develop in a wide range of temperatures (20°C to 45°C) and humidity (45% to 90%) (Karagodin, Yurina, Bastrakov & Ushakova, 2017). BSFL development time varies depending on the diet, temperature, feeding rate and humidity (Diener et al., 2011). This period could be extended up to four months in case of food shortage. In 1995, Sheppard, Larry, Thompson & Savage found out that BSFL can reduce manure waste by 50% during the larval stages. Most of the pests that consume waste carry bacteria or diseases unlike the BSFL which are capable of inactivating pathogens such as Salmonella Spp.(Lalander, Diener, Zurbrugg & Vinneras, 2015) and Escherichia coli.

The prepupal stage is the final larval stage of BSF which is important in waste transformation. Additionally, the BSF prepupae can be self-harvested by redirecting their natural migration to dark dry pupation sites into harvest bins without search for complicated harvest methods (Diener et al., 2011) . However, all the other stages are equally important, though they are not directly linked to biomass conversion. This is because growth and developmental anomalies at any stage affects all the stages and thus the food conversion. Prepupae are dark brown in colour and migrate from the food source to a dry and dark place. This migration enables their harvesting for either breeding into adults or for processing into biofuel oil and animal feed protein. Sheppard et al. (1994) mentions that the prepupae can climb inclines of approximately 40 degrees and crawl 100m upwards to find a suitable pupation place. Pupation is the final stage before emergence of adult BSF and takes approximately two weeks inclusive of the prepupal stage. This time period vary depending on feed availability (Sheppard, Newton, Thompson & Savage, 1994). The pupa then develops into adult BSF which are poor flyers and lethargic thus completing their life cycle according as shown in Figure 2.

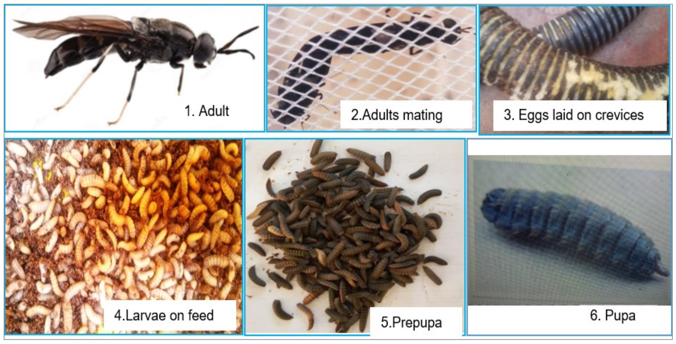


Figure 2: *Lifecycle of a Black Soldier Fly (Matheka et al., 2021)*

The stages of interest in this study are the larvae and prepupa. The use of BSF larvae to consume fecal wastes leads to waste reduction and a larval biomass. Caligiani et al. (2018) reported that BSFL was a good source of nutrients like proteins, lipids, minerals. The high protein and fat content of dried soldier fly prepupae reinforces its high potential as fly meal in animal feed production.

A BSF biowaste processing facility consists of waste pre-processing (consisting of separation of inorganics, particle size reduction and dewatering) , biowaste treatment by BSFL, separation of larvae from process residue, and finally, refinement of the harvested larvae and residue into marketable products (Dortmans, Diener, Verstappen & Zurbrugg, 2017). In addition, a healthy adult and larval nursery should be maintained so as to ensure a reliable and consistent colony (Dortmans et al., 2017) for larval supply.

Benefits of Black Soldier Fly

a) Environmental management

Sustainable utilization, including recycling and valorization, is becoming increasingly relevant in environmental management (Pang et al., 2020). BSF larvae develops on biodegradable waste reducing environmental pollution and converting bio waste into larval biomass. Newton et al. (2005) reported that the BSF technology can potentially reduce pollution by 50 -60% or more. BSFL has been suggested as an effective insect for converting a variety of decaying plant and animal matter including chicken, swine and cattle manure (Newton et al., 2005, Sheppard et al., 1994), waste plant tissues, food waste, municipal garbage and animal offal into insect biomass (Diener et al., 2011, Nguyen et al., 2015) which is a useful ingredient for animal feed. BSFL is able to convert municipal organic waste materials into valuable and less harmful biomass resulting in 65-75% waste reduction (Diener et al., 2011). Recent studies have highlighted that the adoption of BSFL for waste processing can achieve: (i) 30-80% reduction of nitrogen and phosphorus contents (Oonincx et al., 2015, Newton et al., 2005) which minimize eutrophication in water bodies and (ii) volume reduction of the biowaste that ranges from 38 to 74% (Gold, Tomberlin, Diener, Zurbrugg & Mathys, 2018).

BSFL composting is an alternative waste treatment method which can potentially increase revenue from food waste management (Ermolaev, Lalander & Vinneras, 2019). The amount of Waste Reduction (WR) in kitchen waste, fish rendering and a mixture of fruits and vegetables was 67.9, 74.2, and 98.9% respectively (Nguyen et al., 2015). This clearly indicates that there is a great promise for using BSFL as a potential agent for organic waste management. Previous studies have shown increasing efficiencies with time as shown in Table 1 which indicates that reduction efficiencies will improve through continued research and improved optimization of BSF process parameters and conditions.

Leachate from landfills is rich in nutrients and organic by-products resulting to high chemical oxygen demand. The current biotechnologies for treating organic leachate rely mostly on chemical mineralization and microbial decomposition with the main focus being water purification rather than nutrients and energy recycling (Aziz, Aziz, Bashir & Mojiri, 2014, Safari et al., 2011). However, mineralizing leachates using chemical and microbial biotechnologies is a lengthy and costly process. A study by Popa & Green (2012) demonstrated that BSFL could be a potential alternative to offset the cost and clean-up of organic solutes in leachate waste streams while recycling carbon, nitrogen, and phosphate into usable and commercially valuable biomass. As a result, pollution of the receiving waters would be greatly reduced.

Plant biomass used for phytoextraction is usually polluted with heavy metals which is an environmental problem. Thus, plant biomass should be pretreated by composting, compaction or pyrolysis which are time-consuming, expensive or require a specialized equipment so as to remove the excess water and reduce its volume (Sas-Nowosielska et al., 2004). A study by Bulak et al. (2018) revealed that the BSF larvae reduced the dry mass of polluted corn leaves by an average of 49% for both Cadmium and Zinc after 36 days which is a better result compared to composting. Thus, the use of BSF for entomoremediation and as a new method for the postharvest management of plant biomass polluted with heavy metals creates a possibility of its application in the metal recovery process. Laboratory experiments conducted by Diener et al. (2011) showed that BSFL can significantly reduce sludge biomass. Banks et al. (2014) found out that use of BSFL could be a possible solution to the health problems related to poor sanitation and improper fecal waste management in low- and middle-income countries.

Besides the yield of prepupae, the BSF treatment process generates the digestate or residue as the second product (Diener, Zurbrügg, Roa Gutiérrez, Nguyen, Koottatep & Tockner, 2011). The residue has to be post-treated through composting or vermicomposting to ensure biological stability before its use as a soil conditioner and fertilizer or its remaining energy potential is exploited through anaerobic digestion for biogas production (Dortmans et al., 2017, Lohri et al., 2017). In addition, the residue can be used as an innovative and alternative ingredient for new potted plants growing media thus reducing the use of both peat and synthetic fertilizers in soilless production (Setti et al., 2019). The digestate can be used as biochar thus reducing the fluxes of greenhouse gases through anthropogenic activity and increase carbon sequestration (Rehman & Razzaq, 2017).

One of the biggest problems the society is facing currently is the production of Greenhouse Gases (GHG) which is a cause of climate change. BSFL is a novel biological raw material for biofuel production (Zheng, Li, Zhang & Yu, 2012) leading to reduced GHG and lower ammonia emissions than conventional livestock (Van Huis, 2013, Oonincx et al., 2010). Ermolaev, Lalander & Vinneras (2019) found out that total direct GHG emissions from BSFL composting of food waste were comparatively low with carbon dioxide being the major GHG emitted (total emissions of 96 g CO2 per Kg of food waste treated). Chen et al. (2019) reported that BSFL treatment is an alternative for decreasing CH4, N2O and NH3 emissions (by 72.63–99.99%, 99.68%–99.91% and 82.30–89.92% respectively) and reducing global warming potential. Approximately 30% of waste grown BSF larval biomass can be extracted as crude fat which can be used for the production of environmentally friendly lubricants and biodiesel (Li et al., 2011) which make waste-to-energy technology more practical. The oil derived from BSF has a high concentration of medium chain saturated fatty acids (67% total fatty acids) and low concentration of polyunsaturated fatty acids (13% total fatty acids) which makes it a potential ideal substrate for production of high quality biodiesel (Surendra et al., 2016). The BSFL remains after biodiesel extraction can be used in animal feed formulation as a protein source. In addition, the use of abundant and inexpensive organic waste as feed for BSFL is an alternative to conventional crop oil-based biodiesel which causes agricultural land competition and increased food prices thus threatening food security (Li et al., 2011, Zheng et al., 2012). In addition, BSF maximizes the benefits of waste management by reusing the organic waste nutrients for insect growth.

During long processes of organic waste biodegradation, Carbon (C) and Nitrogen (N) are substantially lost (in the form of N2O and CH4) thus reducing the quality of the end-products and causing secondary environmental pollution (Pang et al., 2020). Besides, BSFL can recycle 1.95–13.41% and 5.40–18.93% of the C and N in the food waste into stable insect biomass that can be harvested and preserved (Pang et al., 2020). This can provide a short-term means of sequestration for C and N instead of allowing their release in gaseous form after microbial decomposition, thus keeping low environmental footprint. Thus, the BSF technology is beneficial in freeing up space in landfills, potentially saving on large amounts of transportation costs while producing value added end products. Organic waste used as a feed substrate for the insect larvae lowers their environmental footprint and boost their utility. Therefore, the BSFL recycling technology has lower environmental impact and ecological footprint for protein feed production and other nutrient supplements.

b) Animal Feed Ingredient

The increasing global populations and change in human diets have resulted in an urgent need for additional protein supplies from sustainable sources for inclusion in animal feed and reduction in the strong competition for food and feed. The growing global demand for proteins and lipids cannot be met by the intensive use of agricultural land currently available (Müller, Wolf & Gutzeit, 2017). As needs for food and feed increase, it is important to consider sustainable production systems that include waste reuse and valorization. Using biowaste as substrate for BSF rearing as protein source in animal feed is a very promising alternative (Nyakeri, Ogola, Ayieko & Amimo, 2017) as shown by different studies in Table 1. BSF larvae can feed on various organic substrates characterized by a variety of nutrients producing an energy-efficient high-quality protein source for feed/food (Surendra et al., 2016, Van Huis, 2015), 31-33% fat (Diener et al., 2009) and chitin . In comparison to cattle and swine, the BSFL has a lower feed to protein conversion ratio (Oonincx et al., 2015), and even for poultry according to Van Huis (2013). BSFL can substitute expensive protein sources used in animal compound diet formulation such as soybean and fish meal, which has the potential to reduce future food and feed insecurity (Liu et al., 2017). The larvae's chemical content changes depending on the constituents of waste used as a feed and the stage at which they are harvested (Liu et al., 2017, Spranghers et al., 2017).

threshold, the environment becomes fatal to the larval population (Diener et al., 2011).

Diet/Feed type	Waste Reduction (%)	Crude protein (%)	Reference
Laying hen manure	50	42	(Sheppard et al., 1994)
Swine	50	43.2	(Sepinwall, 2017)
Poultry	50	42.1	
Wild (Bondo area, Kenya)	-	40	(Nyakeri et al., 2017)
Biogas digestate	-	42.2	(Spranghers et al., 2017)
Restaurant waste (vegan)	-	43.1	
Vegetable waste	-	39.9	
Human feces	48.6	27.1	(Gold et al., 2020)
Human feces (Meru, Kenya)	83.3	33	(Matheka et al., 2021)

Table 1: *Percent Waste Reduction and Crude Protein from Different Studies. (Matheka et al., 8687)*

This nutritional profile indicates that embracing resource recovery through BSF technology can contribute to a sustainable protein substitute, environmental hygiene and sanitation. Use of insect protein for animal feed formulation would directly and indirectly provide suitable, sustainable meat demand for the growing global population. The fat fraction can be extracted and converted into biodiesel (Li et al., 2011) while the chitin can be processed to chelating agents which are used in various applications ranging from wastewater treatment to bioactive coatings. Inoculation of BSFL on chicken manure resulted in 50% waste reduction, 42% protein and 35% fat feedstuff (Sheppard et al., 1994). Previous studies which have used different feed substrates for BSF report that protein content in mature larvae comprises between 37.06 and 49.18% dry matter (Jucker, Lupi, Moore, Leonardi & Savoldelli, 2020, Lalander et al., 2019, Spranghers et al., 2017). In addition, the larval and bacterial activity reduces several nutrient contents such as nitrogen and phosphorus (Diener, Zurbrügg, Gutiérrez, Nguyen, Koottatep & Tockner, 2011). The insects' short life cycle increases its reliability as a source of food for fish, chicken and other potential farm animals.

Rearing of BSF is advantageous over other insects due to its ability to efficiently convert biowaste into food thus generating value and closing nutrient loops as they reduce pollution and costs. Moreover, BSF rearing uses less water compared to animal husbandry. BSF species is extremely resistant thus capable of dealing with demanding environmental conditions, such as food shortage or oxygen deficiency (Diener et al., 2011). However, if the waste source turns anaerobic, temperatures reach lethal values or exposure to high heavy metal concentrations exceeding a certain-

c) Reduction of Odor

Odor reduction is achieved by the voracious appetite and high larval density of the BSFL making the waste to be processed in a short time. Furthermore, the larvae excrete dry organic matter and suppress the growth of bacteria (Diener et al., 2011, Van Huis, 2013). With such a combination of characteristics, offensive odors such as indoles, phenols and volatile fatty acids are reduced (Beskin et al., 2018). A study by Lalander et al. (2013) revealed that BSFL has the ability to inactivate the zoonotic bacteria such as Salmonella spp. thus reducing the risk of disease transmission from animal to human. This makes the BSF residue safe enough for use as an organic fertilizer in crop production

d) Reduction of House Fly

House fly, botanically called Musca domestica have feeding parts and searches for food, both organic waste and human food making it interact more often with human beings. Contrary, BSF lack attraction to humans, their habitations and food (Van Huis, 2013) due to the fact that it does not feed but lives on fat stored in its body from the larval and prepupal stages making BSF to be far from being a nuisance. BSF larvae reduce oviposition of house fly which is a disease-spreading insect thus reducing the housefly population. It has been documented by Sheppard et al. (1994) that BSFL colonization of pig and poultry manure had the capacity to reduce common housefly population by 94-100%.

Conclusion

Biowaste treatment and valorization stimulate waste collection through the creation of products with economic value thus returning resources to the economy by using a circular approach which is crucial for sustainable development. BSF larvae is valuable when used in recycling biotechnologies that aim to combine the clean-up of organically rich waste streams with the recycling of energy and nutrients. In addition, diverting organic waste disposal from landfills reduces the release of methane, a potent greenhouse gas into the environment. Therefore, BSF waste treatment constitutes the missing link in designing a circular economy by addressing food security and waste management which are major global challenges.

Acknowledgements

Authors are grateful to Jomo Kenyatta University of Agriculture and Technology particularly the Department of Soil, Water and Environmental Engineering for the continued support during the preparation of this manuscript.

Competing interests

Authors have declared that no competing interests exist.

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