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Review

Reversing the nutrient drain through urban insect farming—opportunities and challenges

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Abstract: Cities consume the majority of proteins produced globally but have unsustainable, linear food systems from production to consumption to disposal, resulting in significant nutrient losses. The industrial rearing of insects is a promising strategy for converting otherwise lost nutrients back into protein-rich animal feed and fertilizer, particularly to supplement local food production. The black soldier fly (BSF), *Hermetia illucens*, has been identified as a candidate for industrial rearing. BSF has a superior feed conversion ratio and cycle-time compared to other edible insects and can convert and recover nutrients from a vast variety of organic materials to protein, oil and chitin making it an attractive solution for the management of urban organic solid waste. With an increasing awareness of the environmental urgency and interest in the economic potential of the technology, this review discusses the technological factors confounding the upscaling of insect farming in urban and peri-urban contexts using BSF as a case study. These include the challenges of feed homogenisation and pre-treatment, of integrating insect life-cycle factors (e.g. mating) with bioprocess engineering concepts (which complicates automation), of meeting the nutritional requirements of the larvae at different stages of growth in order to maximize bioconversion and product quality, and of elucidating the impact of microbiome on complex behaviours and bioconversion. A multidisciplinary effort is therefore required to lead urban insect farming to full development to ultimately contribute to future food security.

Keywords: organic waste valorisation; nutrient recycling; animal feed; alternative protein source; process optimization; black soldier fly (BSF); fish meal replacement

1. Introduction

The world population is expected to increase to and plateau at 9 billion people by 2050, with approximately 70% of it projected to be urban [1]. The urban population is associated with higher income and an increased demand for animal protein. The conversion efficiency of plant to animal matter is ~10%, demanding a significant amount of plant-derived feed [2]. Fishmeal, another major protein feed ingredient, is highly volatile in price and supply and is seen as a significant cause for overfishing and habitat destruction [3]. With a larger and more affluent population concentrated in urban areas, global food demand will surge by at least 60% above 2006 levels, adding immense pressure to the food supply system [4,5]. Food producers are experiencing greater challenges with increasing competition for land, water and energy and the need to curb environmental destruction from the agricultural sector is evident [6]. Climate change furthermore has an alarming implication on crop yield, fish stocks and animal health and productivity and is a threat that will likely intensify over time [4,7]. Therefore, an immediate change in the way food is produced, processed and distributed is required, with the constrained conditions of finite natural resources like never before.

Cities are major consumption hubs, with nutrients in the form of food syphoned and channelled into them from afar, either from dislocated farm areas or abroad. The packaging, preservation and transportation involved have a large carbon footprint. Yet a substantial portion of the food is discarded, representing a waste of resources which can make up between 20 and 80% of municipal solid waste that is either incinerated or landfilled [8,9]. Approximately 30–40% of food produced for human consumption is lost to waste across the food supply chain, amounting to 1.3 billion tons per year [10]. Downstream food wastage associated with consumption correlates to income with city residents generating significantly more waste per capita compared to their rural counterparts [9]. In developing countries, urban solid waste management on its own is a serious environmental problem confronting urban governments due to inadequate collection and treatment [11]. Food waste is rich in nutrients and uncontrolled decay creates serious issues such as groundwater contamination and greenhouse gas emissions. Reducing and recovering losses and waste in the food production chain of cities is one way to improve efficiency, reduce emissions and contribute to food security.

Recycling organic waste material using insect larvae has received much attention due to their ability to concentrate nutrients in low-grade and diffuse organic waste into high quality proteins that can be used for animal feed formulation [12–14]. It is estimated that over one billion tons of compound feed was produced globally in 2017, which was worth more than US$ 460 billion [15,16]. Protein is the staple component for feed formulation systems. For the livestock feed industry, soya bean meal is the principle source of protein. It accounts for approximately 75% of all protein used in livestock feed globally which competes directly with human consumption [17]. In addition to the livestock industry, the aquaculture industry is also growing rapidly and is a major consumer and competitor for feed resources. Fish meal and oil are still considered the most nutritious and digestible ingredients for farmed fish feeds which consumes almost 10% of the world’s fish production [15,18,19]. Soybean and fish meal are both highly traded products produced in excess by only a handful of countries in the world, with the rest of the world importing. Five countries (USA, Argentina, Brazil, China and India) share more than 90% of the world’s total soybean production, which is distributed across 50 countries for industrial feed production [17,20]. For fishmeal, almost 65% of production originates from the top 6 producers (Peru, EU, Vietnam, China, Chile, Thailand) [21]. The combination of increased demand and slowing production has also increased the price of feed ingredients and thus promoted the search for alternative protein sources [22,23]. Insects have the potential to fill this “protein trade-deficit” by adding local and decentralised means of protein production and recycling nutrients within an economy/region. This could also potentially reduce price and supply variability.

While the nutritional value of edible insect is variable due to the vast range of species, most insects have a crude protein content higher than 30% per dry matter and are also rich in energy, fat, minerals and vitamins [24,25]. Their production also requires a significantly smaller environmental footprint and feed conversion efficiency is higher compared to livestock. Thus less space is involved with higher throughput-production and shorter cycle times [26]. While specific legislative rules concerning the use of insect for feed were largely absent or ambiguous in the past, proteins from seven insect species have recently been authorised as feed ingredients in aquaculture by the European Commission Regulation No. 2017/893. Insect meal is also expected to be approved in the European Union for pig and poultry feed by 2020 [27]. Among the authorised species, Black Soldier Fly (BSF), *Hermetia illucens* is one of the most promising for industrial rearing. BSF goes through distinct egg, larval, pupal and adult stages of growth with a relatively short life cycle of 40 to 45 days [28]. They are distributed worldwide and thrive particularly in the equatorial climate [28]. The adults do not ingest or disseminate diseases [29], they are not a pest to plants, do not bite or sting. The larvae are detrivorous omnivores and can process an immense variety of organic material including problematic organic wastes such as faecal sludge, municipal waste, food scrapes, restaurant and market waste, plant residues [30,31]. They convert them into biomass consisting mainly of high quality protein, fat and chitin. The residual larvae excrements, known as frass, contains nutrients and organic matter that can be used as fertiliser and soil conditioner with added economic value (depending on the initial feedstock) [26]. Furthermore, the oils from the BSF larvae can be extracted and converted to biodiesel by, for example, acid-catalyzed esterification and subsequent alkaline-catalyzed transesterification [32].

Despite the commercial prospects of insect farming, mass insect production is still a relatively new industry. While a basic understanding is attained to the extent that enables domestication, there is still substantial potential for productivity optimization regarding the various aspects of rearing and feed conversion efficiency, particularly on heterogeneous urban feedstocks. Production consistency therefore lags behind traditional livestock farming. However, the high density rearing conditions offer an advantage over traditional livestock farming, whereby rearing systems can be engineered and customized for each stage of the life cycle based on both optimized process parameters and good biological understanding. Centralised or decentralised insect bioconversion systems can thus be tailored and integrated solutions for the management of organic solid waste and platforms to recover nutrients as part of urban or peri-urban agriculture systems. In this paper, we discuss some of the challenges in implementing insect farming for urban or peri-urban nutrient cycling following a brief description of the key components in the operation of insect larvae production facility, using BSF as a case study.

2. Major operational components of BSF farming

BSF farming can be split into four major operational components: Feedstock preparation, reproduction and breeding, bioconversion/larvae production and downstream processing (Figure 1). In urban environments, these components can be enclosed in factories that can be deployed into ready-built industrial units. Air ventilation systems, enhanced with air scrubbers can be incorporated into these facilities to remove volatile organic compounds andammonia before discharge for odour control in urban settings.

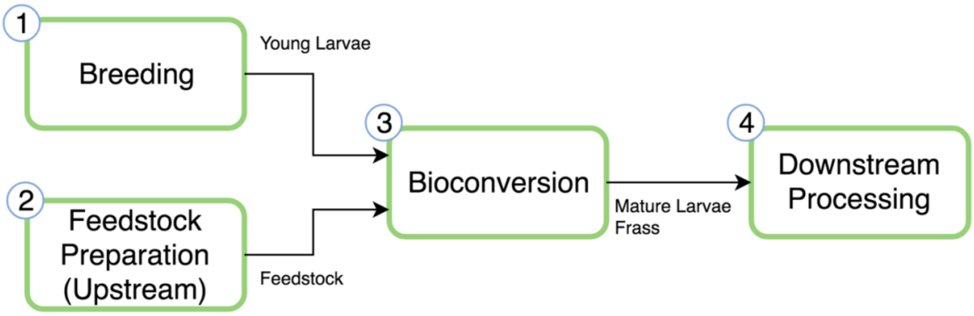

Figure 1. Major operational components of BSF farming (cc Protenga).

Feedstock preparation encompasses the pre-treatment and processing of the organic input material with the objective to manipulate one or more parameters, such as moisture, particle size, texture, sterilization, homogenization and nutritional value. Which specific treatments are necessary is usually dependent on feedstock and downstream methods used. The reproduction and breeding components cover the whole life-cycle of the black soldier fly (Figure 2) with the objective to provide sufficient supply of eggs or young larvae for the bioconversion. While traditional, smaller farming setups often rely on inoculation from the local wild BSF population, most modern farming systems are based on controlled breeding operations to supply the required amount of eggs/young larvae in order to achieve the daily larvae production or waste management targets. Depending on the size and purpose of the facility, some farms not equipped with reproduction and breeding components could instead purchase eggs or young larvae from other facilities.

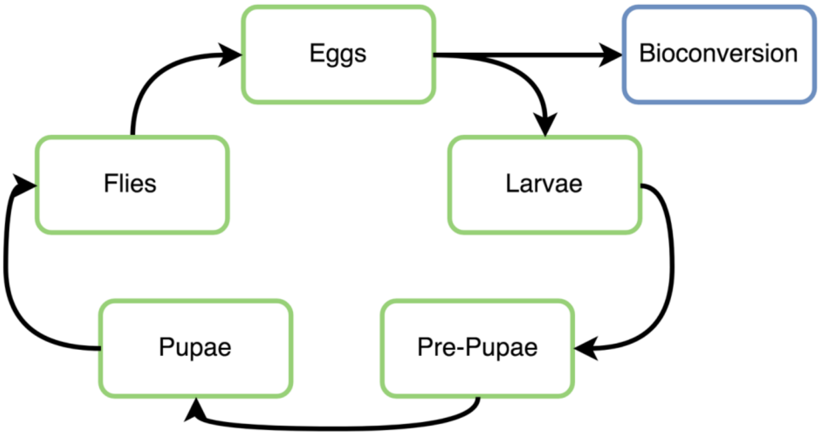

Figure 2. Life-cycle of the Black Soldier Fly covered in the breeding component (cc Protenga).

During bioconversion, the larvae are fed with the feedstock; they build up biomass by extracting valuable nutrients and degrade the input material. While there is a diversity of designs for bioconversion available, some form of container unit usually forms the basic building block of the system. Depending on method, these containers vary in size and shape including large concrete pans, standard plastic trays, and a variety of customized trays (such as “self-harvest” trays) made of materials such as wood, plastics, stainless steel and concrete. Configurations are diverse and no clear dominant design has emerged as of yet: It can be arranged horizontally on the floor or stacked vertically; in sheltered, but open or fully enclosed and often climate controlled facilities; with one-time feeding or multiple feedings; with self-harvest or forced-harvest, etc. At the end of the bioconversion process, there are usually two main product streams, the insect frass and residues, which can be used as a fertilizer and the fresh larvae. Both these product streams can be further refined into a variety of marketable product formats (both as ingredients and final products) during downstream processing.

3. Operational and design challenges for urban and peri-urban BSF farming systems

3.1. Organic waste segregation and logistics

The cost of substrate for bioconversion is one of the most critical factors determining the financial viability of BSF farming. While organic waste is plentiful in urban areas, with a higher amount of post-consumer waste than rural areas, there is a problem with feed consistency, in terms of load, nutrient, organic and moisture content and texture, as well as non-organic contaminants such as plastics. Such variability can have big implications for growth rates, developmental time and downstream processing, which makes stable process control and operation challenging. The type of substrate has been shown to significantly impact both the developmental rate and nutritional composition of BSF larvae [33]. Moisture content has a significant impact on nutrient availability and larval growth rates and subsequent separation of mature larvae from the frass [11,34,35]. While high moisture has been shown to increase growth rates, it also causes aggregation of particles which could hinder separation of mature larvae from frass [35]. Accelerated breakdown of substrate with high nutrient loading and moisture content can also lead to temperature spike beyond the lethal level of 47 ^{o}C, severely affecting survival rate [36]. Standardisation of process feed is thus required to maintain stable operation. This can be achieved by either having a “clean” organic waste from pre-consumer food production by-products or dry agricultural waste where moisture content can be adjusted within the range of 40 and 80% prior to feeding. Ideally the feed will be consistent, in terms of hydraulic and organic loads, with a high content of carbohydrates and proteins, a particle size of <10 mm and moisture content of 40–80% and secured year-round. Post-consumer food waste generally has fast rates of putrefaction, resulting in odor problems and potential propagation of food-borne pathogens or toxins. Therefore, upstream sorting (i.e. quality control) and equalisation of crude organic waste, or a combination of physical and biological treatments, such as homogenisation and pre-fermentation, respectively will be necessary for waste stabilization and to increase food safety. In addition, most nutrients present in agricultural residue or byproducts are in insoluble form and pre-fermentation can enhance the digestibility and bioavailability of nutrients to the insect larvae [37].

While the value of BSF farming is due to its ability to simultaneously treat a challenging (i.e. post-consumer) waste and generate a protein and oil-rich product, given the necessity of pre-treatment and sorting depending on the type of organic waste, the business model and financial opportunities of commercial BSF farming may be largely defined by the regulatory framework of the country. BSF processing systems with a waste management focus achieving high throughput bioconversion of heterogeneous waste can only be financially viable if waste disposal has an enforced cost and regulation, as is the case in China, Australia and many OECD-member countries. Otherwise, the costs associated with aggregating and processing post-consumer food waste to a consistency suitable for BSF larvae bioconversion might be more expensive than the cost of commercial feed. In addition, local waste collection framework can either be individually engaged by commercial entities or centrally imposed by local government, with collectively enforced payments. In the latter case, BSF farms would require to work with the main concessionary rather than the actual waste sources. Alternatively, the focus would have to be on generating revenue from producing high quality and consistent downstream products in terms of size and appearance of larvae and also its nutritional content. This can be achieved using pre-consumer feedstocks as is the case in the European Union and the United States. In both scenarios, transportation cost of waste is another major consideration and therefore BSF farming operation may need to be operated with a combination of centralised and decentralised facilities whereby the bioconversion unit would be located in close proximity to the source of waste.

3.2. Optimization of nutrition, feed rate and load

A major limitation with regards to optimising pre-treatments, bioconversion and feeding practices, is that current methods for characterising the impact of larval feed on conversion efficiency and growth are largely empirical. Feed is understood in terms of the type of waste (e.g. fruit waste, vegetable waste, faecal matter) with some macronutrient characterisation and performance referenced against chicken feed or the Gainesville diet [33,34,38–40], as opposed to more fundamental indices used to assess the nutritional value of feed (e.g. in livestock), such as digestibility, energy content, amino acids and fatty acids, vitamins and minerals. In addition, process control and monitoring of BSF rearing studies is often non-standardized. Operational parameters known to play a key role in bioconversions are often left uncontrolled or unreported, such as pH [41], larval density [42], food-to-larvae ratio [40], temperature [43], nitrogen conversions and feeding rates [11]. Not only does this contribute to great variability in terms of bioconversion duration and efficiency, it confounds the interpretation of rearing studies with respect to understanding the impact of nutrition and feeding practices. For example, the developmental time of BSF larvae was found to vary between 15.9 to 42.2 days depending on the feeding rate with the same substrate [11]. Furthermore, nutritional demands of the larvae change according to the stage of the life cycle [44]. Feeding practices should be modulated according to stage of growth (i.e. neonates versus prepupae stage), however this is currently poorly understood. Thus, there is much scope to optimise feeding practices and enhance productivity and bioconversions of BSF larvae rearing schemes.

3.3. Requirement for semi-automated systems

The need for automation depends on the labour cost of the region. Most production processes are highly labour intensive. While this could be viable in some economies such as bioconversion facilities in Indonesia [45], given the general higher cost of labour and problem of land scarcity in urban relative to non-urban areas, in order for BSF larvae rearing to be a viable technology, a shift towards process automation is required. BSF farming is a biological conversion process, for which there are many analogous processes that have been implemented successfully and at an industrial scale across the world, including waste water treatment, anaerobic digestion, and bioethanol production. All such processes are very mature, stable in operation, implemented across a range of scales and contexts, and optimised intensively due to the application of sound process engineering practices, including monitoring and modelling. This enables fully automated bioprocesses. It is worth considering, therefore, what has held BSF back from achieving dominant designs for process automation.

One major reason is the increased complexity and variability of dealing with higher-order organisms (i.e. insects) which display more nuanced behavioural traits, particularly regarding pupation, mating and sexual selection, unlike bacteria of course which reproduce asexually. Another factor, still largely not understood, is the contribution to BSF behaviours and life cycle of symbiotic microorganisms elaborated in the next section. Finally, the complexities of insect behaviours and life cycle mean that the development of the process has been largely driven by entomologists rather than biotechnologist or process engineers. Better integration between the study of insect behaviours and good engineering practices [46] is required in order to develop the technology towards benchmarked best-practices and accepted automation models.

Nevertheless, several means of automation can already be adopted and improvised from other waste treatment or industrial processes such as upstream waste sorting, feeding devices and separation of mature larvae from substrate. Process monitoring to determine efficiency losses along the whole production train is crucial for process optimization. This includes determining the percentage of viable eggs, survival rates of neonate, pupation rate and hatching rate. In addition, managing standardized larval densities and feeding practices are also important process elements. Such monitoring and control processes are still often carried out through manual counting, weighing, assumption-based calculations and extrapolation, which is time consuming and error prone. Automating these processes can increase significantly the ease and stability of operation, assist in identifying bottlenecks and prevent or provide early-notice of potential biological infection or contamination instances. However, process automation will significantly increase the upfront capital expenditure relative to labour intensive processes and hence cost-benefit and breakeven analyses will ultimately be required to evaluate the optimum process design.

3.4. Understanding the structure and function of the BSF gut microbiota

Insects are considered the most successful living animal clade on planet comprising about 95% of all known animal species [47]. Their diversification and evolutionary success is closely linked to their infinite relationships with symbiotic microorganisms that are known to improve nutrient-poor diets; increase digestibility of recalcitrant food components; protection from predators, parasites and pathogens; governs mating and reproduction systems; and thermal tolerance [48].

In the digestive tract, microbial communities play a prominent role in essentially all animals. This has been extensively investigated in humans [49] and farmed animals [50] but generally lacking in industrially reared insects such as BSF. Investigations of the gut microbiota of only a limited number of insect taxa thus far have revealed the critical role of gut microorganisms in nutrition, physiology, immune response and pathogen resistance [48]. The microorganisms in the insect gut can be highly complex comprising of protists, fungi, archaea, and bacteria which can be maternally transmitted, acquired from social interaction or from the environment such as diet [48]. Little is known on the role of gut microbiota on the physiology of BSF though a study shown that bacteria isolated from the BSF eggs significantly enhanced oviposition when the culture was used as an attractant [51]. However, the composition of bacteria coevolving in the substrate can override and colonize the host gut microbiome in other insects such as drosophila potentially affecting nutrient acquisition and growth [52], preliminary study also suggests similar interaction in BSF [53] but further investigation is required to establish mechanistic understanding. In addition to larvae development, BSF larvae are able to express a wide spectrum of antimicrobial peptides many of which are induced by bacterial load in the feedstock and the types of diet [54]. This could potentially contribute to the reduction of unfavourable bacteria such as *Escherichia coli* and *Salmonella enterica* in the substrate [55,56]. The ability of BSF larvae to grow and utilize a range of organic substrates raises intriguing questions toward the structure and function of their gut microbiome which can be exploited for the development of probiotic or cultures that can be used for bio-augmentation to enhance the breakdown of specific waste streams or improve growth, development, reproduction and immunity leading to overall process optimization. These capabilities and characteristics of BSF appear particularly promising in the context of urban and post-consumer waste recycling using BSF cultures, both in terms of ensuring biosecurity and extraction optimization.

4. Conclusions

While various biological treatment processes have been developed and applied to treat organic wastes, insect bioconversion alone allows for the recapture of nutrient losses in the food supply chain. Nutrients are converted directly to proteins coincident with mitigation of organic waste production, thus enabling a circular economy. This is especially attractive in urban settings that have a high rate of organic waste production. Insect protein produced from organic waste is a sustainable alternative to current protein sources for compound feeds in the livestock, poultry and aquaculture industries. However, considering the immense size of the feed market, production of insect biomass needs to be stable and significantly increased in volume for it to be an economically competitive replacement. In addition, the end product also needs to be consistent in quality and safe. To achieve this, we have highlighted in this review some challenging aspects of rearing and production that can only be solved with an integrated approach involving regulators, entomologists, bioprocess engineers, industry and end users.

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Conflict of interest

The authors declare no conflict of interest.

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