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Insect-Based Bioconversion: Value from Food Waste

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Introduction

As detritivores and herbivores, the diversity of insect species includes groups highly specialized in their ability to thrive on different organic substrates as food sources. Some of these substrates resemble food wastes from agriculture and food processing industries. In the literature, this is referred to as insects-based “bioconversion” and represents an economically viable method for turning large quantities of food waste into valuable materials—including feed for animals (insect biomass as a supplement added to animal feed), food for people, secondary industrial compounds (biofuel, lubricants, pharmaceuticals, dyes, etc.), and the leftover food waste can be used as organic matter and nutrient-rich

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soil amendments. Consequently, the services rendered from insect-based bioconversion provide marketable solutions for reducing food waste that are fiscally manageable, modest both in space and energy requirements, environmentally friendly, associated with real market/commercial opportunities, and yielding higher feed conversion ratios than conventional livestock (Li et al. 2013; van Huis and Oonincx 2017). Though a relatively nascent industrial sector, mass production of insects for feed and secondary products is a rapidly growing enterprise with significant potential for growth (Dossey et al. 2016; van Huis and Oonincx 2017). Presently, only a few insect species are commercially used for insect-based bioconversion of food waste, with black soldier fly larvae (*Hermetia illucens* L.) being the most commonly used species (Wang and Shelomi 2017). This is juxtaposed by the immense diversity of insects adapted to a wide range of food sources and therefore likely capable of providing effective bioconversion of a wide range of food waste materials. Considering the diversity of food waste streams generated from numerous crop varieties and their by-products from downstream processing, there appears to be ample opportunity for exploration of optimized combinations of food wastes-to-insect pairings to maximize both bioconversion and insect biomass production. In this chapter, we argue better food waste-to-insect pairings and selective breeding of insects are needed to increase capacity of using insects-based bioconversion of food waste. In addition, we provide both theoretical and practical solutions (businesses), and regulatory hurdles relating to insect-based bioconversion of food waste.

The Case for Insects—Why Bioconversion of Food Waste?

insect-based bioconversion of food waste is the controlled breakdown of an initial feedstock (food waste) into insect biomass and frass (waste residuals) (Barry 2004), with the latter consisting of predominantly insect frass and to a lesser extent, shed exoskeletons, dead insect parts, and potentially uneaten feedstock. The process of insect-based

bioconversion of food waste mirrors the natural breakdown of organic matter in ecosystems (Lim et al. 2016). In such systems, naturally occurring insects, earthworms, a wide range of other invertebrates, fungi, and bacteria colonize and break down food waste, converting the nutrients for their own metabolic and reproductive needs. Under controlled conditions, the species responsible for the decomposition process can be regulated and the ambient conditions can be optimized to favour the growth and bioconversion by the given species performing the service. Importantly, value may be produced at multiple steps in the bioconversion process (Barry 2004). For instance, value can be gained from the elimination of the initial waste itself (Mutafela 2015) (disposal fees), sales of insect biomass for food and feed (Anankware et al. 2015), sales from fractionated secondary products (Zheng, Li, et al. 2012), and sales of the remaining bioconverted waste for soil amendments (Suantika et al. 2017). Industrial insect rearing can efficiently turn many tonnes of food waste feedstock into valuable products, with some sources suggesting most food waste can be diverted to insect-based bioconversion (Ortiz et al. 2016; Veldkamp et al. 2012). Currently, Agriprotein's South African facility has the capacity to process 72 megagram (Mg) tonnes of food waste each day, in turn generating 16 Mg of "insect meal" (dried powder from ground insect biomass), 9 Mg of insect oil, and 88 Mg of fertilizer (www.agriprotein.com). Agriprotein uses black soldier fly for its food waste bioconversion and is looking into using other species as they expand. They are one of several companies in the rapidly expanding insect-based bioconversion sector, with others including Ynsect (www.ynsect.com), Nextalim (www.nextalim.com), UNIQUE (www.gzunique.com.cn), and Alapre (www.insectmeal.com.co).

Commercialization of insect-based bioconversion represents a promising shift in providing alternative options for food waste reduction (Nyakeri et al. 2017; Wang and Shelomi 2017), as the industrial production of insects requires significant quantities of cheap, reliable feedstock (Ortiz et al. 2016). With supplies of global food waste estimated at 1.3 billion tonnes and growing (Ambuko 2014; FAO 2017), and demands for protein, biofuels, and fertilizers increasing (Parfitt et al. 2010), businesses adopting insect-based bioconversion make economic sense (Barry 2004). Moreover, insect-based bioconversion of otherwise

disposable food wastes provides a much-needed link for recirculating nutrients and resources from consumers back into agricultural supply chains. With consumers evermore concerned about the environmental profile of goods, insect-based bioconversion of waste is a marketable asset that may appeal to the sustainably minded customer (D'Souza et al. 2007). On a philosophical level, the concept of insect-based bioconversion hinges on the notion of completely re-thinking the concept of "food waste". In the Webster's English Dictionary, "waste" is defined as "an unwanted by-product". The Food and Agriculture Organization of the United Nations makes a further distinction between "food loss" (early stages of the food supply chain) and "food waste" (later in the food supply chain) (FAO 2017). The concept of insect-based bioconversion means that by-products from one food production system become the input in bioconversion systems, so the concept of "waste" and "loss" really cannot be applied. Thus, the trend trail-blazed by insect-based bioconversion and described in this chapter represents a re-thinking of nutrient and resource flows within and among food production systems, and it is expected to become a critical part of more sustainable food production systems in the twenty-first century.

Waste-to-Insect Pairings

While the most commonly used species of bioconverters may be very suitable in some situations, one species cannot adequately capitalize on the immense diversity of food waste streams (Lardé 1990; Smetana et al. 2016). Within the diversity of insects, there are undoubtedly species with specific attributes that make them uniquely suited as bioconverters of a highly specialized food waste. To optimize pairings of insect species and food waste, one must consider a combination of abiotic interactions and functional traits of the insect for handling the waste. Abiotic attributes are non-living chemical and physical characteristics of the food waste (i.e. moisture content, phenolics, nutrient load, etc.). Whereas, functional attributes of insects include: feeding behaviour, morphology (i.e. large mandibles (mouth part) for masticating, soft bodies for moving through substrates, behavioural avoidance of poor

egg laying sites), development time, ability to resist diseases, and a range of other attributes. It is the combination of these abiotic and functional attributes that allow some insects to be well suited for bioconversion of waste, while rendering others as maladapted (Fig. 12.1).

For example, vegetative food wastes can be fed to both black soldier fly larvae and mealworm larvae (Li et al. 2013; Manurung et al. 2016), but this waste is too low in protein content for housefly larvae (Hogsette 1992). Conversely, restaurant and kitchen wastes containing meat are well suited for housefly and black soldier fly larvae, but are too wet for mealworms, which can get moisture directly from the air and thus perform optimally in drier wastes (Cheng et al. 2017). Further, black soldier fly larvae tolerance of wet wastes and high temperatures (from bacterial and colony metabolism) allow them to capitalize on many waste streams (Table 12.1). But husbandry practices also require specific lighting for breeding, the flies are intolerant to temperature drops, and perform poorly in some low nutrient wastes (beet pulp

Fig. 12.1 Two adult black Soldier flies. Adults live only a couple of weeks, while they mate and lay eggs (a). Black soldier fly larvae on restaurant waste (b). Once growing to their full size, larvae exhibit self-extraction behaviours and move away from their food source

Table 12.1 Some insects used for bioconversion, the different wastes that they can be fed, and the final products

Species	Organic wastes	Country	Bioconversion output	Reference
Black soldier fly (<i>Hermetia illucens</i>)	Rice straw, restaurant waste (3:7)	China	Biofuel	Zheng, Hou, et al. (2012)
	Rice straw	Indonesia	Biomass	Manurung et al. (2016)
	Coffee pulp, husk	El Salvador, Indonesia	Biomass, fertilizer	Lardé (1990), Suantika et al. (2017)
	Waste from pears, banana, and cucumber (5:3:2)	Sweden	Biomass	Mutafela (2015)
	Corn stover	China	Biofuel, soil amendment	Wang et al. (2017)
	Corn cob	China	Biofuel	Li et al. (2015)
	Sorghum	United States	Biomass	Tinder et al. (2017)
	Cowpea	United States	Biomass	Tinder et al. (2017)
	Cassava peel	Indonesia	Biomass	Supriyatna et al. (2016)
	Vegetable trimmings, spent coffee grounds, and tea leaves	United States, Hong Kong	Biomass	Cheng (2016)
Housefly (<i>Musca domestica</i>)	Vegetables, peels of yam, cassava, plantain	Ghana	Biomass	Bonso (2013)
	Restaurant waste (70%)	China	Biomass, biofuel, fertilizer	Niu et al. (2017)
Codling moth (<i>Cydia pomonella</i>)	Corn silage, sawdust (30%)			
	Starch and cheese wastewater sludge	Canada	Biomass	Brar et al. (2008)

(continued)

Table 12.1 (continued)

Species	Organic wastes	Country	Bioconversion output	Reference
Cambodian field crickets (<i>Teleogryllus testaceus</i>)	Cassava plant tops, spent grain, mung bean sprout waste, field weeds	Cambodia	Biomass	Miech et al. (2016)
Yellow Mealworm (<i>Tenebrio molitor</i>)	Wheat straw, bruised cabbage leaves	China	Biomass	
	Corn stover	China	Biofuel	Wang et al. (2017)

(Smetana et al. 2016)). This combination of abiotic interactions and functional traits of the flies translate to actual economic trade-offs, as drying food wastes and using special equipment (lights) add costs to commercial operations. As such, considering appropriate waste-to-insect pairings is a significant component in using insects in food waste reduction. Table 12.1 illustrates examples of appropriate waste-to-insect pairings, while not an exhaustive list, it highlights the extent to which more insects should be studied for their potential bioconversion performance. Table 12.1 also includes products of economic value generated from bioconversion, with the inclusion of less commonly used insect species.

Selective Breeding

Due to their short lifespans, high reproductive rates, and variable genetic expression, insect adaptation (evolution) may occur within economically relevant time scales (Jensen et al. 2017). When adaptation is controlled by humans, the process is referred to as artificial selection or selective breeding and will play an important role in developing/engineering insect lines for bioconverting specific food wastes (Jensen et al. 2017). For example, some by-products of food processing are high in plant defensive chemicals and are largely inedible.

These “recalcitrant” food wastes may be high in tannins and phenolics (for instance, the chemicals partially responsible for the specific/unique tastes associated with wine, cranberries, coffee, chocolate, and cinnamon) and are difficult to bioconvert using insects. These chemicals are plant adaptations evolved to repel or even kill herbivores (van Dyk et al. 2013). However, studies focusing on insect-plant defensive interactions have demonstrated insects can be adapted to detoxify these chemicals (Carroll et al. 1998; De Jong and Bijma 2002). Using selective breeding, insects could be bred to overcome defensive chemicals found in recalcitrant wastes and thus allow for bioconversion of troublesome food wastes (e.g. wine and olive pomace). Other examples of insect breeding may include, improving germplines to increase yields of secondary products (oils and pharmaceuticals) (Li et al. 2012), larger body size (Jensen et al. 2017), and shifts to novel food sources (Alves et al. 2016).

Selective breeding in industrial mass production of insect occurs actively or passively (Jensen et al. 2017). Passive selective breeding involves permitting mated females to self-select waste oviposition (eggs laying) sites across generations. For breeding and bioconversion operations, female self-selection may pose a cost-efficient method for capitalizing on insect instinctive (innate) survival behaviours (Nansen et al. 2016). For example, silkworm “innate recognition templates” are programmed to specific chemical cues that indicate the best food for her offspring even after thousands of years of domestication (Garlapow et al. 2015). Active selective breeding involves forming separate lines for each waste and using inbreeding, linebreeding, and outcrossing to control gene expression (Jensen et al. 2017). In general, active selective breeding requires more maintenance and containment and therefore can be cost prohibitive for some operations. However, active selective breeding is more controlled, which may appeal to capital intensive operations, and it represents an opportunity to develop and commercialize specific insect strains. In conclusion, insect breeding for more efficient food waste reduction is still in a preliminary phase academically, which contrasts to the proprietary lines already used by commercial enterprises. Nevertheless, as businesses continue to develop around industrial insect production there will be more funding and research interest in advanced insect breeding programs.

Business Processes

Food waste may be viewed as a problem by some, but others view it as an appealing opportunity for business. The last two decades have seen an explosion of growth in businesses using insects to convert food waste (Table 12.2). Yet, businesses centred on the mass production of insects have existed for centuries (honey bees, silk moths, lacquer bugs) (van Huis 2013). Additionally, many businesses developed in second half of the twentieth century selling insects for biocontrol, medical research, and for supporting the pet trade (Ortiz et al. 2016). Drawing on research and methods developed for mass production of insects for other purposes, new companies are finding significant opportunities producing insects for feed and food. An indispensable component for these businesses is acquisition of inexpensive, abundant, and consistent sources of feedstock, and for many the preferred and economical choice is food waste.

In the following, we describe the basic design of mass production of insects for bioconversion, with different steps for producing valuable materials (Fig. 12.2, steps 1–11). Operations begin with an incoming food waste feedstock (1). Food waste feedstock may require pre-processing before it can be used as feedstock for the given insects (2). Some pre-consumer food wastes like juice pulps are already processed and can therefore go directly into the bioconversion process. Once the feedstock is ready, insect inoculum is added either as eggs or as small immatures (3). For all insect species, most of the growth and bioconversion occurs during the immature stages. To optimize biomass production, the ideal harvesting time is during late (well-developed) immature stages. Harvesting/extraction (4) may be done by mechanically sifting immatures from frass; however, some insects have self-extraction behaviours which allow them to be collected by controlling their evacuation routes. The sifted frass may then be further broken down via microbial decay (10) or mixed with additives and packaged as a fertilizer (7). Depending on the business, populations of extracted insects may be sold live (5) or further refined into valuable commodities such as biodiesel, defatted insect meal, pharmaceuticals, etc. (6–7).

Fig. 12.2 Typical business process for insect-based bioconversion of food waste. Note that value can be extracted from both the elimination of waste and downstream materials, such as insect protein (biomass), oils, frass, and pharmaceutical ingredients (Image is modified from an original design by www.eawag.ch/ and licensed under CC BY 2.0.)

In addition, each of these steps may require external inputs of electricity, water, labour, etc. (11). It should be noted that there is a range of opportunities provided within the production chain, from high-valued small-volume products to low-value bulk commodities. Below, we briefly review some of the possible revenue streams from insect bioconversion systems.

Bioconversion to Produce Fertilizers

The chemical and physical properties of insect frass used as a fertilizer are compatible to other commercial products (Salomone et al. 2017). For example, in one study the growth rate and chemical composition of cabbages grown using black soldier fly frass were identical to commercial fertilizers (Choi et al. 2009). Similarly, onion production was identical for both insect frass and compost amendments (Zahn 2017). This may be due to the added ammonia (NH_4^+) from nitrogen in insect

Table 12.2 Examples of insect bioconversion companies. Reduction rates estimated from a Feed Conversion Ratio of 1.7 and 68% moisture content of extracted larvae

Company	Food waste eliminated	Daily reduction (estimate)	Insects used	Products sold	Country	Founded (year)
Agriprotein	Pre- and post-consumer organic waste	72 Mg	Black soldier fly	Protein feed ingredient (MagMeal™), oil feed ingredient (MagOil™) and compost (MagSoil™)	South Africa	2008
Nextalim	100% traceable EU approved by-products	41 Mg	Black soldier fly	Insect fertilizer, black soldier fly larvae live or dried, black soldier fly larvae defatted proteins and BSF oil	France	2013
Alapre	Organic waste and animal by-products	24 Mg	Black soldier fly	Insect meal and compost sold under the trademark "ENTHOS"	Colombia	2014

(continued)

Table 12.2 (continued)

Company	Food waste eliminated	Daily reduction (estimate)	Insects used	Products sold	Country	Founded (year)
Proti-farm	Vegetable by-products	confidential	Lesser mealworm + various	Various applications with focus on food: buffalo's frozen, freeze-dried, grinded (EntoPure)	Netherlands	1978
Entofood	100% vegetable by-products	240 kg	Black soldier fly	Whole insect meal, defatted insect meal, insect oil	Malaysia	2012
Insectum	Former food-stuff including milk and eggs	22 kg	Black soldier fly	Black soldier fly larvae frozen, dried and/or defatted	Lithuania	2016
Nextprotein	Organic inconsumable food matter	4.5 Mg	Black soldier fly	Insect protein meal, oil, and fertilizer	France/Tunisia	2015
Hermetia	Bruised rye	4.3 Mg	Black soldier fly	Dried larvae, insect meal, insect oil, fertilizer	Germany	2006

(continued)

Table 12.2 (continued)

Company	Food waste eliminated	Daily reduction (estimate)	Insects used	Products sold	Country	Founded (year)
F4F	Pre-consumer organic waste	1.3 Mg	Black soldier fly	Starter feed functional ingredients (fish and poultry), exotic pet snacks, fertilizer and feed development trials	Chile	2014
Innovafeed	Cereal by-products	1.1 Mg	Black soldier fly	Defatted meal and purified fat of black soldier fly larvae	France	2015
Enterra feed	Pre-consumer recycled food products	confidential	Black soldier fly	Whole dried larvae, meal, and oil	Canada	2007
Ynsect	Vegetal material only, by-products	confidential	Mealworm	Protein, oil, frass	France	2011

frass, which has been shown to increase fivefold relative to the non-fertilized plants (Green and Popa 2012). In addition, benefits of insect frass compost include reduction of pathogenic microbes and pesticides (Lalander et al. 2016). However, there are concerns that heavy metals may accumulate in the frass of some insects (Diener et al. 2015).

Bioconversion for Biodiesel

Biodiesel is a promising non-fossil fuel; however, concerns about the resources diverted for its production have sparked debate over a reliance on oilseeds, which require large tracts of arable land and impact food prices. Insects are an alternative source for generating precursors for biodiesel (fats and oils), due to immature insect's predisposal for sequestering high energy fat prior to pupating into adults (Manzano-Agugliaro et al. 2012). In addition, food wastes that are naturally high in fat such as palm oil cake and restaurant waste may be used as a feedstock with the added benefit of reducing the food waste problem while generating sustainable biodiesel. The methodology for producing biodiesel from insects is similar to producing biodiesel from other biological fat sources (Fig. 12.3) (Tyson and McCormick 2006).

Fat contents harvested from insects vary between species, food waste source, and development stage—with the larval stage containing the highest fat content (Manzano-Agugliaro et al. 2012). The immatures of many species have fat contents above 25%, with some in excess of 77% (moth, *Phassus triangularis*) (Manzano-Agugliaro et al. 2012). Biodiesel yields can be doubled by first pre-extracting fats from the food waste,

Fig. 12.3 Representative process for production of insect biodiesel

then feeding the post-extraction remains (solid residual fraction) to insect immatures that are later harvested (Yang et al. 2012; Zheng, Li, et al. 2012). Examples of insects used for biodiesel production include; black soldier fly larvae with added microbes (Rid-X) to convert rice straw (30%) and restaurant waste (70%), producing 43.8 g of biodiesel from 1 kg of waste (Zheng, Li, et al. 2012); yellow mealworm larvae fed decaying vegetables and dry leaves, producing 34.2 g of biodiesel from 234.8 g of dried mealworm larval biomass (Zheng et al. 2013); yellow mealworms fed fruit waste and palm oil cake (Leong et al. 2016); latrine fly larvae (*Chrysomya megacephala* Fabricius) and common housefly (*Musca domestica*), fed restaurant waste were ~24% and ~20–35% oil by dry weight, respectively; flesh fly (*Boettcherisca peregrine*) fed solid residual fraction of restaurant waste (~31% oil by weight) (Yang et al. 2012). Finally, indicative of the interwoven utility of insect-based bioconversion, one study found waste corn cobs too lignified for direct consumption by black soldier fly larvae were first fermented anaerobically, then given to black soldier fly larvae to make biodiesel—resulting in 87 L of biogas and 3 g of biodiesel from 400 g of corncobs (Li et al. 2015). In conclusion, many steps in insect-based bioconversion of food waste can be used for extraction of fuel sources, providing an alternative to our finite fossil fuel resources.

Bioconversion for Food and Feed

Human populations are expected to exceed 9 billion before the next century; this will accompany a 60–70% increase in consumption of animal products (Godfray et al. 2010). Insect-based bioconversion of food waste has the potential for supplementing future protein demands and is an extremely underutilized resource (van Huis 2013). As such, multiple agencies including the FAO, European Union, and U.S. Department of Agriculture encourage the use of insect protein as a logical component for feeding future populations (FAO 2017; Mlcek et al. 2014). However, despite their support, current legislative and oversight infrastructure are underdeveloped for human consumption (EFSA 2015) (see section ‘Regulations’). Instead, insect protein is entering

markets as animal feed, and a growing number of companies use food waste as the feedstock to sustain their operations (Table 12.2).

For animal feeds, the most well studied and commonly used species are black soldier fly larvae, house fly, mealworms, and crickets. Black soldier fly larvae are an especially lucrative feed source, rich in protein and fat, with faster development than other species used for bioconversion (Wang and Shelomi 2017). When ground into insect meal they may be used as a replacement for soya- and fishmeals in many animal feeds. Studies have shown that they are suitable for monogastric animals such as pigs, poultry, freshwater prawns, and some fish species, but not suitable for alligators, some frogs, or ruminants (cows) (Makkar et al. 2014). Larvae fed fish offal from processing plants were on average 30% lipid, of which 3% was omega-3 fatty acids (St-Hilaire et al. 2007). Table 12.1 lists a wide range of food wastes used as feedstock for black soldier fly larvae (and other insects) processed into animal feed. A life cycle assessment from one pilot bioconversion facility employing black soldier fly larvae for food waste treatment found 10 megagram (Mg) tonnes of food waste input, generated 0.3 Mg of dried larvae and 3.3 Mg of compost (Salomone et al. 2017). These results are consistent with figures provided from large full-scale operations such as Agriprotein and Nextalim (Table 12.2).

In animal production, comparison of inputs to outputs is referred to as the Feed Conversion Ratio (FCR), with the inverse being the Conversion of Ingested food (ECI) (Waldbauer 1968). Low FCRs indicate higher efficiencies and therefore conversion of the food waste into animal biomass. The literature on conventional livestock feed often uses the FCR, which we will also use to compare insects to other livestock. Studies have found the following FCRs for insects: black soldier fly larvae = 1.4–2.6, mealworms = 4.1–19.1, and crickets = 2.3–10.0 (Oonincx et al. 2015). In comparison, conventional livestock FCRs are: poultry = 2.3, pork = 4.0, and beef = 8.8 (Wilkinson 2011). This suggests, it takes a larger quantity of feed to produce a kg of beef or pork than it takes to produce a kg of insects. For example, if 100 kg of restaurant food waste was fed to black soldier fly larvae, chickens, or a cow, the food waste would yield 58 kg of black soldier fly larvae, 25 kg of chicken, or 2.9 kg of beef. It should be noted that the FCR of

insects can be highly variable depending on the source feedstock and density of insect populations. However, using average FCR of black soldier fly larvae, we can assess how much income would be generated per unit of food waste. For example, assuming an FCR for black soldier fly larvae of 1.7, a filled refuse truck (21 m³) with 50 Mg of food waste, yields ~29 Mg of prepupae (62% moisture content), which can be dried into ~11 Mg of dry larvae (Diener et al. 2009). At the price of 995 €·Mg⁻¹ (1131 \$·Mg⁻¹), this would yield € 11,000 (\$12,500) (Salomone et al. 2017) each truckload. Insect-based bioconversion of food waste therefore is an appealing opportunity for producing marketable proteins, while simultaneously mitigating the negative impacts of food waste.

Regulations

Commercialization of output materials from insect bioconversion requires a high degree of confidence in their safety. Due to the novelty of industrially mass-produced insects for food and feed, risks of associated contaminants entering the food chain warrant investigation and oversight. In anticipation of new products making their way into European markets, the European Food Standards Agency (EFSA) has published an opinion on the risk profile of insects as food and feed, concluding that food and feed products should pose no greater threat than products already on the market (EFSA 2015). Further, the agency highlighted the need for continued research in microbial, chemical, and allergenic hazards, as well as impacts on processing, storage, and environmental hazards (EFSA 2015). This has been welcoming news for stakeholders of insect-derived products, demonstrating increased legitimacy and legislative consistency for the growing economic sector. However, significant legal hurdles remain, for example, the European Union prohibits insect meal as feed for pigs and poultry, but not aquaculture (Regulation EC No. 999/2001), it is prohibited to use catering waste as feed stock (Regulation EC No. 1069/2009); and insects must be “slaughtered” off-site (Regulation EC No. 1099/2002). In addition, the United States and European Union consider some insects as

“mini-livestock”, thus affording protections against inhumane slaughter (Vantomme et al. 2012).

Research into the chemical safety concerns has been mostly positive, for example many insects accumulate chemical contaminants (pesticides, heavy metals, pharmaceuticals, dioxins, and mycotoxins) below recommended maximum concentrations suggested by the European Commission and World Health Organization (Charlton et al. 2015; Lalander et al. 2016; Purschke et al. 2017). However, examples of toxic heavy metal accumulation have been documented for house fly (i.e. cadmium) (Charlton et al. 2015), blowfly (*Calliphora sp.*) (mercury) (Nuorteva and Nuorteva 1982), and black soldier fly (lead) (Purschke et al. 2017). Recommended measures ensuring end product safety include monitoring the food waste feedstock, as well as the insects produced (Purschke et al. 2017). In the case of microbial contamination, highly competitive “pestiferous” species such as black soldier fly secretes antimicrobial compounds into the wastes they feed in (Park et al. 2014; Sheppard et al. 2007). These secretions limit and can even prevent hazardous pathogens like *E. coli* and *Salmonella* in the waste (Erickson et al. 2004; Lalander et al. 2015). These antimicrobial properties are highly beneficial for the bioconversion of municipal food waste, due to the wastes’ heterogeneous states of decomposition.

Regulations on producing animal feeds were not designed with insect meals in mind. As laws come under review, amendments likely will be added to permit more biologically informed oversight. Overall, insects used for food and feed are considered safe (Belluco et al. 2013). This is consistent with insects’ role as an integral component of many animals diets, and humans long history of consuming insects both intentionally and inadvertently (Center for Food Safety & Applied Nutrition 1995; DeFoliart 1992).

Conclusion

Insect-based bioconversion of food waste offers an exciting vision for a more sustainable future and for novel paths to sustainable food production and food security. Insect-based bioconversion is particularly

exciting, because it enables food and feed production in densely populated areas (urban settings) and therefore goes against the common notion that urban development and food production are antagonistic. After many years of advocating the potential of developing industrial scale operations to tackle food waste (van Huis 2013; Wang and Shelomi 2017), insect-based bioconversion companies are now being established and their throughput is reaching scale, becoming profitable, and moving into international markets. This next decade will see considerable growth in this sector, bringing jobs, novel commodities, new inputs to the food and feed supply, and ultimately reduction and reuse of food waste streams currently considered problematic. For this vision to materialize, research is needed to find more food waste-to-insect pairings, as well as selective breeding to develop specialized insect strains. Both are needed to increase capacity and to maximize the potential benefits of using insect-based bioconversion of food waste. The risks posed by the development of high-performance insect strains for food waste elimination are small, as many of the commercial insect species used for bioconversion are naturally occurring globally (mealworms, black soldier fly). Research is needed to bridge the gap between enterprises engaged in insect-based bioconversion and the regulatory agencies keeping us safe. More studies on the safety of insect-derived products are likely to lead to biologically informed policy. With the proper checks, insect-based bioconversion of food waste has the potential to serve as a powerful tool to eliminate food waste, create jobs, and provide an environmentally friendly source of protein to help feed our ever-growing global population.

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