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ABSTRACT

Food loss and waste are serious threats to the sustainability of our food systems. Innovative and multifaced solutions are continuously being proposed, tested and implemented by researchers, government authorities, non-government bodies and food industries to tackle this problem of food waste. Insect-based bioconversions have been reported as a marketable solution for reducing food waste. This rather novel approach can efficiently convert several tonnes of food waste into valuable products including human food, animal feed, fertiliser and other secondary industrial compounds. This paper couples the production of edible insects with the valorisation of food waste, providing an attractive key for closing the loop of food value chain. Current status of insect processing and their importance in circular economy is also discussed in detail.

Contents

1. Introduction

Food loss and waste are serious threats to the sustainability of our food systems. According to the Food and Agriculture Organisation of the United Nations (FAO), roughly one-third of the global food production for human consumption (c.a. 1.3 billion tonnes per year) is lost or wasted (FAO, 2011). One of the Sustainable Development Goals (SDGs) outlined by United Nations' in 2015 intends to 'halve the per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses' by 2030. Recently, governments are starting to be aware of it and are implementing food policies to tackle this problem. Policy-makers, food industries and retailers, researchers and non- government organisations are working together to trigger a social movement towards a greater appreciation of food and minimising the overall food waste and its impacts. The first step of an effective food policy

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involves identifying and quantifying the type of wastes. The terms food losses and waste are often used interchangeably, but some studies have tried to differentiate them based on the stages of a food supply chain (Kennard, 2019). Food losses can be defined as the discarded food (produced for human consumption) at the production, post-harvest and processing stages of food supply chain and when it is thrown away by the final users at the retail and consumption levels, it can be termed as food waste (FAO, 2017). The term food waste comprises leftover food generated from agricultural production, postharvest handling and storage, further processing of food, wholesale and retail trade distribution, kitchens of large-scale consumers and private households (Edjabou et al., 2016). A classification of food waste types is proposed in Fig. 1, which considers the sources and modes of food losses and waste generation during the food chain from farm to fork. During agricultural production, losses can be resulted due to mechanical damage and/or spillage during harvest operation; e.g. threshing, fruit picking, etc. Postharvest handling and storage losses include the spillage and degradation during handling, storage and transportation between farm and distribution. Further, industrial or domestic processing of food also generate losses during various unit operations including sorting, washing, peeling, slicing and boiling or because of faults and accidents in process lines. Food distribution at wholesale markets, supermarkets and retailers level also generate losses and waste of food. The last in the value chain is at consumption level, including losses and waste in the home or restaurants/caterer.

Food waste and loss can further be classified into three broad categories – avoidable, partly (optional) avoidable and unavoidable food waste (Kranert et al., 2012). For industry, avoidable food waste includes damaged or contaminated products that have not been used. At household consumer end, avoidable food waste occurs for a number of reasons, including over-purchasing, poor food preparation techniques, inadequate storage and excessive serving sizes (Bagherzadeh et al., 2014). The avoidable component of food waste accounts for a substantial part of the total household waste. For example, a study in Denmark sampled and measured the food waste quantities in 1474 households and reported that the avoidable food waste accounts for ca. 56% of total household food waste (Edjabou et al., 2016). Partly (optional) avoidable food wastes are mainly generated because of different consumer practices and habits, e.g. bread crusts and apple skins. Unavoidable food waste usually arises during the preparation and consumption of foods. This mainly includes both non-edible constituents (e.g. bones, banana peels or the like) and edible parts (e.g. potato peels).

In industrialised countries, majority of the food waste is generated in the later stage of supply chain at consumer level. On a per-capita basis, consumers in Europe waste food between 95 and 115 kg/year (FAO, 2011). In the EU, over 50% of the total food waste generated occurs at the household or consumer level. Other sectors contributing to food waste in the EU are food processing (19%), food services (12%), production (11%), wholesale and retail (5%) (Stenmarck et al., 2016). Thus, in theory at least, the current largest potential for reducing waste lies in the consumer sector. Various research scientists, food banks, government and non-government agencies have proposed and implemented innovative strategies to tackle food waste problem. The core of these strategies is based on three R's of waste management – **R**educe, **R**euse and **R**ecycle. The United States Environmental Protection Agency (EPA) has proposed a waste management hierarchy considering that all materials and waste streams in all circumstances cannot be managed by one single strategy (Sakai et al., 2011). Fig. 2 presents a possible waste management hierarchy ranking the three main waste management strategies and their sub-categories from most to least environmentally preferred measures. Food waste can be reduced by improving each unit of a food chain; mainly, processing, product development, storage, distribution, marketing, labelling and cooking methods. Reuse of food waste can be achieved by creating effective channel between potential food donors to hunger relief organisations. Food waste can be recycled by feeding to livestock, anaerobic digestion, composting and creating bioenergy and natural fertilisers (Thi et al., 2015). Most of the food waste programs developed today tends to focus on structural changes and technological development and often overlook the role of household consumers. Behavioural change of consumers is another potential intervention to minimise household waste. Linder et al.

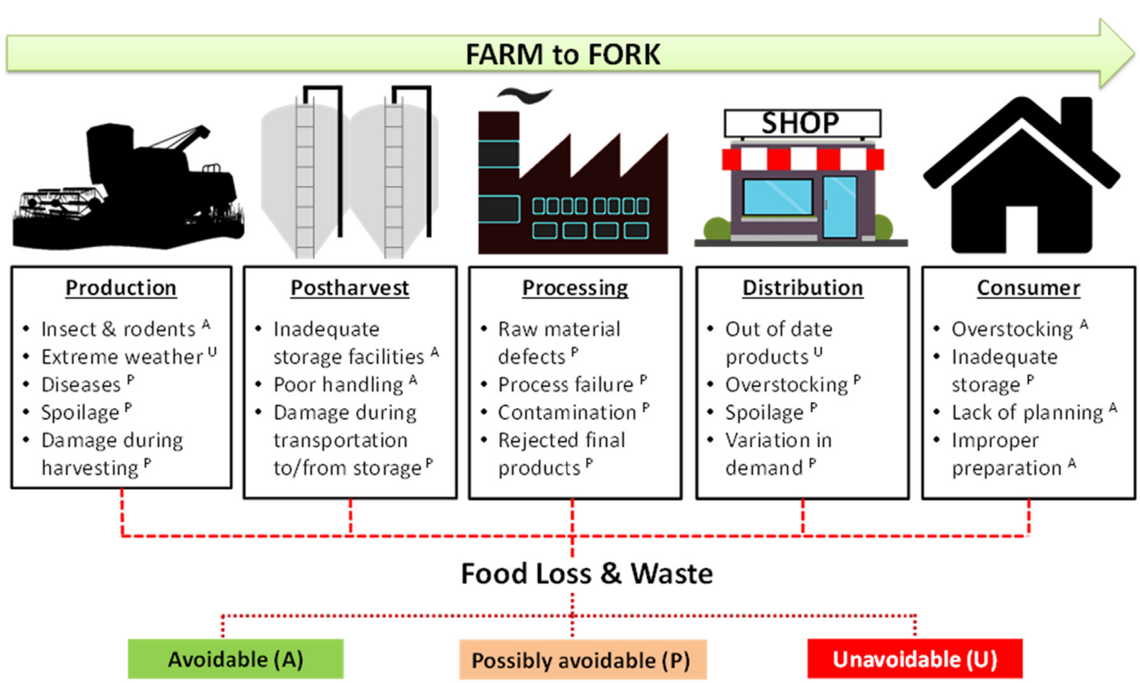

Fig. 1. . Food loss and waste throughout the food chain.

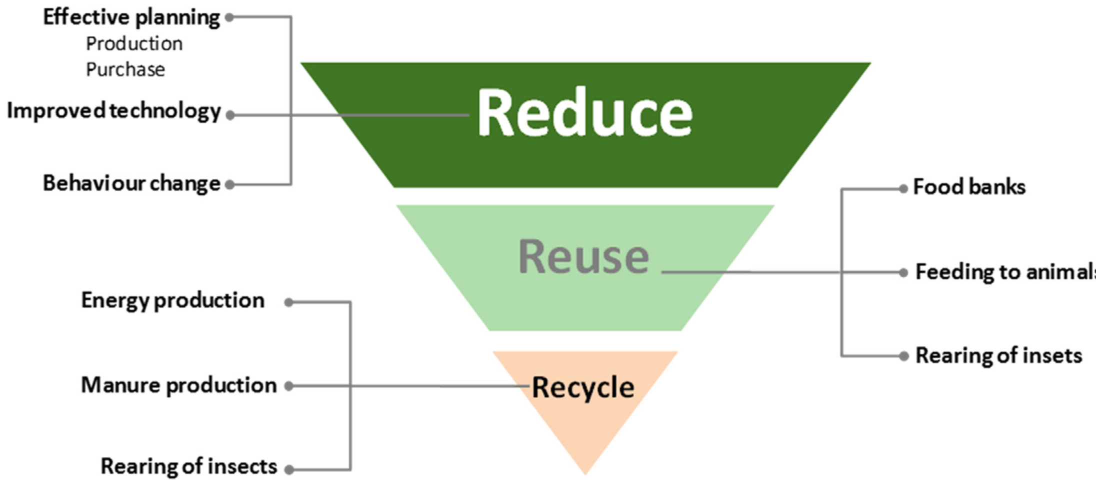

Fig. 2. . Reduce, reuse, recycle concept for food waste.

(2018) conducted a study to test whether an information intervention (a leaflet), designed based on theories from environmental psychology and behavioural economics, can be effective in promoting recycling of food waste in a suburb area of Stockholm city, Sweden. The results indicated a statistically significant increase in food waste recycled compared to a control group in the research area.

Several researchers have proposed using insect-based bioconversion as a marketable solution for reducing food waste which has received increased worldwide attention in recent years (Cheng et al., 2017; van Huis and Oonincx, 2017; Van Huis et al., 2013). This rather novel approach is based on the fact that industrial insect rearing can efficiently convert several tonnes of food waste into valuable products including human food, animal feed, fertiliser and secondary industrial compounds (e.g., biofuel, lubricants, pharmaceuticals, dyes) (Fowles and Nansen, 2020). Being a natural component of the diets of many animals and birds, insects could be used for feeding farmed animals including fish, poultry and pigs (Sogari et al., 2019). In this paper, the potential of coupling the production of edible insects and the valorisation of food waste will be discussed. Current status and future outlook of insect processing and their importance in circular economy is also discussed in detail.

2. Food waste for mass production of insects

The commercial rearing of insects is a promising approach for transforming the nutrients losses back into the food chain in forms of protein-rich animal feed, human food and fertiliser. The black soldier fly (BSF), *Hermetia illucens* is a popular choice for industrial rearing, owing to its short life cycle, superior feed conversion ratio and the fact that it can convert and recover nutrients from a vast variety of organic materials. BSF can reduce organic waste biomass by 50–60% and turn them into high protein biomass (Sheppard et al., 1994). Further, the nutritive profile of BSF larvae is comparable to oilseeds including hempseed, flaxseed and rapeseed with up to 28% of protein and 40% of oil content (Matthäus et al., 2019). Currently, each Agriprotein's facility has developed a capacity of diverting 350 tonnes of food waste per day and producing protein, oil and organic soil conditioner using BSF (www.agriprotein.com). Several other companies and start-ups from all over the world including Entosystem (www.entosystem.com), Protix (www.protix.eu), and Goterra (www.goterra.com.au) are rapidly expanding to address the issue of food waste by insect-based bioconversion.

With supplies of global food waste estimated at 1.3 billion tonnes and growing, commercialisation of insect-based bioconversion represents a promising economic sense for businesses. However, there are some challenges in rearing insects on food waste in a safe and efficient way and hence continuous advancements are being made with insect breeding, rearing diets and conditions for industrial rearing. Optimisation of insect rearing broadly depends on a) composition and consistency of insect feed, b) selection of insects, c) other technological parameters such as rearing conditions, and d) regulatory guidelines (Cortes Ortiz et al., 2016; Vantomme et al., 2012). In specific to rearing insects on food waste; physical, chemical and microbiological characteristics of the food waste including moisture content, nutrient profile and presence of non-preferred compounds, microbial safety, stability and occurrence of non-organic contaminants such as plastics are some of the key parameters to be considered. For example, vegetative food wastes which are generally low in protein content can be used as feed for both black soldier fly larvae and mealworm larvae, but may not be sufficient for housefly larvae (Fowles and Nansen, 2020). Restaurant and kitchen wastes containing meat can be well suited for housefly and black soldier fly larvae (Cheng et al., 2017; Hogsette, 1992; Manurung et al., 2016). Additionally, Cheng et al. (2017) also reported that the black soldier fly larvae can tolerate of wet wastes and high temperatures allowing them to utilise different waste streams. Variability in diets 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 insects (Spranghers et al., 2017). Food wastes are rich in nutrient and water content, hence prone to faster putrefaction, resulting in odour problems and potential proliferation of moulds, foodborne pathogens or toxins. Sorting and optimisation of crude organic waste with a combination of physical and biological treatments, such as homogenisation and pre-fermentation, respectively can be performed for the waste stabilisation and the improved food safety. Pre-fermentation can also help in enhancing the digestibility and bioavailability of nutrients to the insects as most nutrients in raw food waste are found in insoluble form (Law and Wein, 2018). Valorisation of food waste using fermentation and then use of edible insects, especially of the BSF has shown promising results (Alattar et al., 2016).

Further, the selection of suitable insect species with specific attributes; such as feeding behaviour, morphology (i.e. large mouth part for masticating food, soft bodies for moving through substrates, behavioural avoidance of poor egg laying sites), shorter development time and immunity to possible diseases are important considerations for bioconversion of a highly specialised food waste. In addition to the selection of suitable insects, insect breeding can be useful in utilising food waste more efficiently. However, insect breeding research is still in an initial phase and has a huge potential in future with a growth in the insect business in the western countries in the insect business (Fowles and Nansen, 2020). Technological factors such as temperature, humidity and light also influence the rearing of insects.

An important hurdle of using food waste is at the regulatory level. According to European regulations on animal by-products (1069/2009), Article 3, farmed insects are included in the definition of 'farmed animals' (EC, 2009). Hence, insects can only be produced with substrates eligible as feed materials for farmed animals and hence it is prohibited to the use of certain materials such as manure or catering waste containing animal by-products, processed animal protein (except fishmeal). Many agencies, such as Promoting Insects for Human Consumption & Animal Feed (www.ipiff.org) is promoting and advocating towards adapting existing EU policies and legislation, which opens up the possibility of modification of current feed list.

3. Importance of insects in circular economy

Our current food production and consumption habits are unsustainable. Circular economy concept can offer tools to enhance and optimise for sustainability of a food system (Jurgilevich et al., 2016). A sustainable food cycle can have five stages: food production, processing, distribution, food consumption, and food waste management (Wunderlich and Martinez, 2018). If each of these steps is managed properly, we can achieve overall sustainability in food cycle. The purpose of sustainable food systems is to build a better future. The mission is to create sustainable values by providing food products to satisfy the consumer needs while considering the core values of food safety, quality and less environmental impacts. Over the last decade, circular economy has become one of the most important themes worldwide, which fosters the promotion of sustainable and resource-efficient policies for long-term socio-economic and environmental benefits (Milios, 2018). Circular Economy concept aims to overcome the linear pattern of production and consumption by adopting strategies of a circular or "closing the loop" system in industrial production systems (Maina et al., 2017).

As discussed earlier, using the food waste for rearing insects provides an attractive key for closing the loop of food value chain (Fig. 3, see Section 5). Studies have shown that insects may offer significantly better food conversion ratios and require significantly fewer inputs in the form of land, fresh water and feed compared to traditional livestock systems (Oonincx and De Boer, 2012). The other possible environmental advantage of insect farming over livestock production has been described as emit fewer greenhouse gases emission during their cultivation (van Zanten et al., 2015). However, some researchers have shown their concern and demanded for an urgent need of further research before commercial mass production of insects in order to avoid possible environment hazards. These concerns are mainly related to selection of suitable insect species, their housing and feed requirements, managing their waste and possibility of ecosystem imbalance escaping insects from insect farms (Berggren et al., 2019).

There are several tools and methods for evaluating sustainability for a food processing technology and the most recognised environmental assessment method is life cycle assessment (LCA). It is a tool used for the quantitative assessment of inputs, energy flows and environmental impacts of systems, products and services. The basic LCA methodology is based on ISO 14040, consisting of four steps: a) defining the goal and scope, b) creating the life-cycle inventory, c) impact assessemnt, and finally d) result interpretation. In a food system, a full cradle-to-grave LCA would consider each steps starting from production of raw material, processing, manufacturing, delivering, consuming, and managing the end-of-life. Because of the complexity of this approach and the fact that the data for ultimate disposal of food is not included

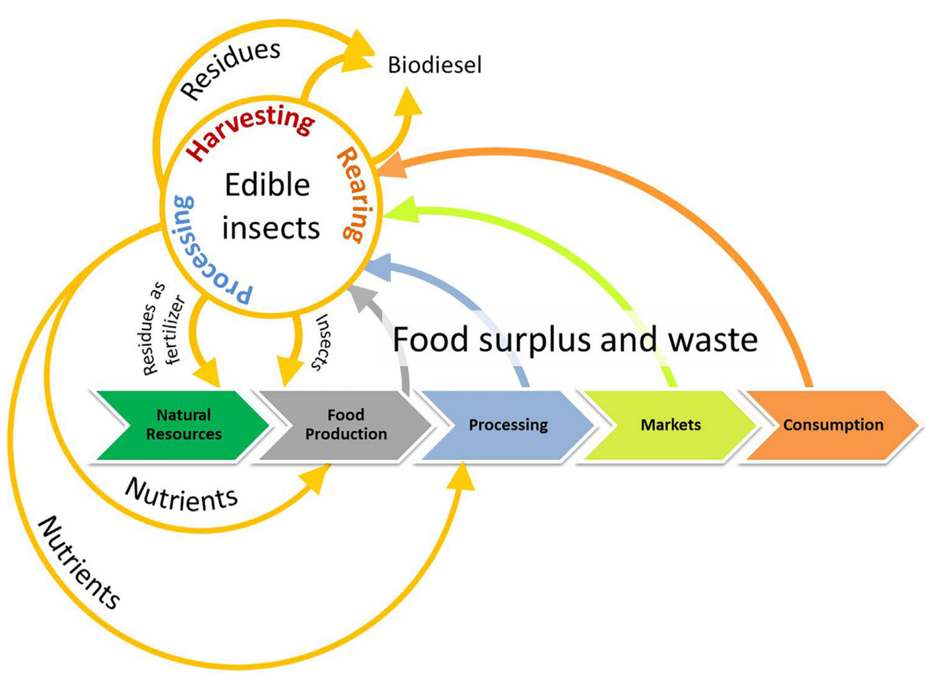

Fig. 3. . Concept of an ideal insects production and processing system integrated in the food chain: the waste from food production, processing and consumption is utilized for insect rearing; reared insects entering the food chain as whole or a nutrient source in food production and processing; the residues from insect rearing and processing serves as natural fertilizer for agricultural crop production. .

Table 1
. Research studies presenting applications of life cycle assessment (LCA) in evaluation of environmental impact of insects for food and feed production systems.

System	Geographical region	System boundaries	Goal and scope	Functional unit	Main environmental impact category	Main findings	References
Commercial mealworm production system	Netherlands	Cradle-to-farm-gate	To compare the environmental impact of producing mealworm and super worm vs. conventional sources of animal protein	Mass based (kg of fresh product and kg of edible protein)	Climate change, energy use, land use	Mealworms produce much less GHG's and require much less land, than chickens, pigs and cattle	(Oonincx & De Boer, 2012)
Laboratory plant for housefly larvae rearing	Netherlands		To assess the environmental impact of organic waste fed common housefly larvae as livestock feed	Mass based (ton of larvae meal on dry matter basis)	Climate change, energy use, land use	Waste fed larvae require less land, however can have indirect consequences including energy use and global warming potential	(van Zanten et al., 2015)
Various systems from database	Global	Cradle-to-plate	To compare environmental performance of different meat substitutes based on data from literature and other sources	Mass based (kg of ready for consumption products, such as fried meat or meat analogue)	climate change, metal and fossil fuel depletion, ozone layer depletion, human toxicity, acidification, ecotoxicity, land occupation	highest impacts for lab-grown meat and mycoprotein-based analogues (high energy demand),medium impacts for chicken, dairy-based and gluten-based meat substitutes, and the lowest impact for insect-based and soy meal-based substitutes	(Smetana et al., 2015)
Industrial scale production of BSF	Germany	Cradle-to-processing gate	to assess the environmental impacts of insect production for both food and feed on an industrial scale	Mass based (kg of dried defatted insect powder and kg of ready-for-consumption fresh product at processing gate)	Climate change, human toxicity acidification, ecotoxicity, ozone Depletion, eutrophication, land occupation	Chicken meat and whey proteins impact is 2–5 times higher than insect products	
Pilot system for food waste bioconversion by BSF	Italy	Cradle-to-gate	to assess the environmental impacts of insect-based feed products fed with different waste products	Mass based (ton of food waste, kg of protein and kg of lipids)	Climate change, acidification, ecotoxicity, human toxicity, ozone Depletion, eutrophication	Higher environmental impacts are caused by compost and feed production followed by the transportation of food waste, higher GWP and energy use and lower land use of insect bioconversion system compared to soy meal and rapeseed oil systems	(Salomone et al., 2017)
Small scale manure and biowaste based production systems of housefly and BSF	West Africa	Cradle to gate	to provide a better understanding of production characteristics and of the factors influencing the systems' performance in specific context of regional small scale insect farming	Mass based (kg of larvae meal on dry matter basis)	Land use, water consumption, fossil energy use,	Black solider fly system has highest conversion efficiency, however the conversion efficiency is dependent on complex interaction of insect species, nutritional properties of the rearing substrate, rearing techniques and climatic conditions.	(Roffeis, et al., 2017)
Medium scale production system for field and house crickets	Thailand	Cradle-to-farm-gate	To compare regional broiler and cricket farming	Mass based (kg of edible mass) and nutritionally based (kg of protein in edible mass)	climate change, acidification, ecotoxicity, eutrophication, ozone depletion, human toxicity, water depletion, mineral and fossil fuel depletion	Overall, the environmental impacts associated with broiler production were greater than for cricket production	(Halloran et al., 2017)
Commercial production system for mealworms	France	Cradle-to-mill gate	to assess environmental impacts associated with production of mealworm meal with high protein content for poultry and trout feed	Mass based (kg of larvae meal)	climate change, acidification potential, eutrophication potential, land use	Mealworm meal production currently had higher environmental impacts, especially energy demand, than production of other sources of protein used in animal feed	(Thévenot et al., 2018)
A highly productive BSF pilot plant with insight on future upscaling	Netherlands and Switzerland	Cradle-to-gate	To assess the environmental effect of food industry side streams transformation into intermediate products for feed and food and to provide guidance to industries to identify most promising directions towards sustainable insect production	Mass based (kg of dried and pelletized organic fertilizer, fresh BSF puree, protein concentrated meal and BSF fat)	climate change, ecosystem, human health, ecotoxicity, global warming, acidification, land occupation, water use, fossil fuel depletion, eutrophication, carcinogens, non-carcinogens, ozone depletion	Fresh insect biomass is almost twice more sustainable than fresh chicken meat and insect production has potential for more sustainable protein, fertilizer and lipid production	(Smetana et al., 2019)

Table 1 (*continued*)

System	Geographical region	System boundaries	Goal and scope	Functional unit	Main environmental impact category	Main findings	References
Commercial BSF kitchen waste treatment system	Indonesia	Cradle-to-gate	to assess the GWP of a BSF waste treatment facility compare to composting facility	Mass based (ton of biowaste)	direct N_2O and CH_4 emission, electricity consumption, GWP	BSF treatment direct GHG emissions were 47 times lower than from windrow composting and fishmeal production substitution by BSF larvae meal can reduce the GWP up to 30%	(Mertenat et al., 2019)
Small scale mealworm meal production system for feed in trout production system	France	Cradle-to-farm gate	To assess the influence of replacing fish meal with mealworm meal (at 0%, 15% and 30% levels) on overall environmental impacts	Mass based (kg of pan-sized trout)	Eutrophication potential, acidification potential, climate change, land use, energy demand, water consumption, biotic resource use	Mealworm meal resulted in lower impact in terms of biotic resource use and water consumption compared to fish meal but did not reduce other environmental impacts	(Le Feon et al., 2019)

GHG- green house gases, GWP- Global warming potential, BSF- black solider fly.

in the analysis, variations of LCA are commonly applied in food systems. These variation could be based on cradle-to-farm out gate (including production of ingredients, agriculture, and initial processing at farm), gate-to-customer (including transportation from farm to factory, processing and packaging, and transportation to customer), and cradle-to-customer or farm-to-fork (including farming, processing and packaging, and transportation to customer) (Morawicki, 2011). The LCAs have only recently been applied to insect rearing systems.

Recently, some research studies have applied LCA for evaluation of environmental impact of insects for food and feed production systems. The main features of these studies are presented in Table 1. The first study on LCA applied to insect farming for human consumption was published in 2012 (Oonincx and De Boer, 2012) which was followed by studies on insect system for animal feed, fish feed, organic fertilizers. Recently, Smetana et al. (2019) performed a LCA of food industry side streams transformation using *Hermetia illucens* into intermediate products applicable for feed and food purposes. Apart from general concepts of insect production and processing, they considered more detailed dataset and included the production of raw materials (feed for *H. illucens*), processing and storage of feed, growth cycle of *H. illucens* (from egg production, larvae hatching, growing and larvae harvesting), and processing of outputs into different products (fresh insect puree, protein concentrate, insect fat and organic fertiliser). The system was considered to be a highly productive pilot plant with insight of future upscaling scenarios. Attributional and consequential LCA approaches were applied for the definition of more sustainable options. The analyses indicated that the fresh insect biomass was nearly twice more sustainable than fresh chicken meat. Such initial studies point toward a lesser environmental impact of insect production; however, there remains a lack of knowledge in this area.

This is still unsure if the insects processing industry will be sustainable and environmentally friendly. From sustainability perspective, the possibility of using food waste which is otherwise unavailable as food for people (e.g., unavoidable food loss and waste) improves the system feed conversion efficiency when viewing insect farming. Insects have a strategic positioning in food value chain. Amongst the grand challenges in sustainable food system, the main challenges ahead of insect processing are development of efficient and environmentally friendly processing technologies, waste minimisation, recovery and incorporation of by-products/ co-products. With abundant research, knowledge and examples from other food sources, insect industry is at the forefront for the development of a set of new best practices to implement a true circular economy and overall sustainability from its foundation.

4. Current status of insect processing

The insect for feed and feed industry is moving ahead at a fast pace. Although edible insects currently have a niche market at this stage with enormous potential which is expected to grow for potential feed and food applications. Global Markets Insights (GMI, 2016) estimates that market volume will increase from initially 33 mm USD in 2015 to 522 mm USD in 2023 which corresponds to a yearly growth rate of 41%. It is estimated yearly growth of 71% from 106 million USD in 2016 to 1.5 bn USD in 2021 (Arcluster, 2016). This enormous growth is primarily driven by insects as a food ingredient in powders and shakes (40% market share) and food bars (28% market share) according to GMI (2016). A number of production and storage strategies have been developed to improve farming of insects and it is now crucial to implement appropriate post-harvesting technologies for the preservation, quality improvement, transformation, fractionation, distribution, and storage of insects and insect products (Melgar-Lalanne et al., 2019a). Processing of insects can vary depending on the application i.e. either consumption of insects as a whole or of biomolecules obtained after suitable fractionation. Historically processing of insects obtained from wild harvest e.g. collection from forests, natural water resources or agriculture fields or reared at commercial scale include boiling, roasting, smoking, frying, stewing and curing to improve nutritional, and sensorial attributes and shelf life of products (Melgar-Lalanne et al., 2019a). Modern manufacturing processes include both conventional and innovative processing techniques. Some of the unit operations applicable to insect processing are blanching, drying, grinding, roasting and fractionation. This list is not exhaustive and other processing techniques, e.g., fermentation, salting and non-thermal technologies can be used to produce variety of insect products as the global appetite for insects increases. The existing processes employed for insects are discussed below:

4.1. Blanching

Most small and larger scale commercialised edible insect processes employ blanching as a pretreatment to inactivate degradative enzymes and to reduce microorganisms responsible for food poisoning and spoilage (Melgar-Lalanne et al., 2019a). Conventionally, it is a process involving a series of steps; mainly placing a food product in boiling water for a short period, removing, and then immediate cooling in ice or cold running water to stop the thermal treatment. Hot water blanching can significantly reduce counts of total mesophilic bacteria, total psychrotrophic bacteria, lactic acid bacteria and yeast and moulds in insects; however, as expected, it has been less effective against mesophilic bacterial spores (Megido et al., 2016; Vandeweyer et al., 2017).

Besides the well-known positive impact of blanching, the hot water blanching can affect the physical and chemical characteristics of food. Specifically to insects, a slight increase in moisture has been reported in several studies. For example, Vandeweyer et al. (2017) reported an increase of moisture content (from 62.81% to 70.44% after 40 s) in In *T. molitor* L. larvae; however the water activity remained constant. They reported the cause to be the absorption and entrapment of water inside the larva just below the chitinous exoskeleton. According to Azzollini et al. (2016), high temperature blanching may result structural changes in some proteins, resulting in alteration, denaturation and crosslinking of protein molecules. However, there are no reports of significant adverse effects in chemical composition in blanched insects compared to fresh ones, which can possibly be attributed to lack of more suitable and specific protein analysis (Azzollini et al., 2016). Additionally, blanching also decreased in luminosity in the samples, which could be because of physical as well as chemical phenomena. The main physical phenomenon was proposed to be the modified refraction index resulting from the higher moisture value in blanched samples when compared to dry samples. The other factor could be solubility of nutrients in blanched samples, which may increase certain secondary reactions, such as non-enzymatic browning reactions, resulting in reduced lightness of blanched larvae.

In last few decades, innovative surface decontamination technologies with higher energy efficiency, less nutrient loss and less environmental impacts are being developed and applied. Innovative blanching technologies including microwave, ohmic, and infrared combined with hot air or steam blanching can also be employed to insects. For example Bußler et al. (2016a) employed surface dielectric-barrier air-discharge plasma for improving microbial safety of *T. molitor* L. and observed a significant reduction in microbial load while improving the techno-functional properties of Tenebrio flour for product applications. Table 2 summarises the research findings in blanching treatments applied to edible insects.

4.2. Drying

Drying is one of the most extensively used technologies for increased shelf-life of foods. Drying techniques have evolved a range of traditional methods (e.g., sun-drying, roasting, and frying) to modern, novel and advanced methods including freeze-drying and hybrid drying technologies. Drying results in reduction of total water content and water activity therefore restrict the availability of free water for degradative enzymatic reactions and microbial growth. Drying results in improved safety and shelf-life during distribution and storage of insect products. Sun-drying, oven-drying and freeze-drying are some of the applied technologies for drying whole edible insects, insect flours and powders (Azzollini et al., 2018; Kröncke et al., 2018; Niassy et al., 2016). Drying followed by grinding the whole edible insects into unrecognisable insect powders has been reported to be one of the preferred technologies for increasing human consumption of insects in western countries (Melgar-Lalanne et al., 2019a).

4.3. Fractionation/extraction

As mentioned earlier, in Western countries, consumer acceptance of eating whole insects is still a major challenge; thus, insect protein in form of powder, supplement or fractions can be more acceptable for human food applications (Caparros Megido et al., 2014). Further, the production of protein rich flour from insects for incorporation into foods provides an opportunity of versatile application of insect protein in human diets.

Extraction of insect macromolecules can be carried out using water, organic solvents, and enzymes and the extraction rate, extraction yields and the physicochemical, functional, and bioactive properties of macromolecules depend on the insect matrix and solvent used (Bußler et al., 2016b). Although many different types of extraction techniques have been tested to recover key macromolecules from insects, however, they rely on using huge amounts of chemical solvents, which is not considered as eco-friendly or food-friendly (L'hocine et al., 2006; Soetemans et al., 2019). The use of clean and green extraction techniques is gaining recognition owning to the consumer demand of chemical/additive free ingredients (Tiwari, 2015). Therefore, it is needed to improve efficiency, reduce costs and develop more environmental friendly processes. Purschke et al. (2018) reported that the pre-treatments (blanching, freezing and thawing) can be employed for dry fractionation of insects based ingredients including protein rich fractions, chitin etc. Employing novel pretreatments in combination with extraction technologies can improve recoveries of key macromolecule from insect matrices. Table 3 presents potential technological solutions for extraction of insect fractions either by physical techniques (dry fractionation) or wet chemistry employing solvents.

5. Concepts to close the cycle

The production of insects, even on formulated diet is reported to be more efficient than rearing some traditional livestock (van Huis and Oonincx, 2017). However, production of insects can result in large quantity of organic waste, consisting of frass, exuviae, and uneaten feed, which is of low value and is commonly disposed of by spreading on agricultural fields (Jucker et al., 2020). The concept of the land application of insect frass enables the reintroduction of insect rearing side stream back into the food production chain, thus is consistent with circular economy's principles. It has been

Table 2
Blanching treatments applied to edible insects.

Insect species	Conditions	Main findings	Reference
Alphitobius diaperinus (beetle)	Submergingin hot water (at 90 °C) until water temperature reaches 88 °C (5 min)	4.0 log cfu/g reduction in total microbial count; no typical pathogens; aerobic endospore count remained unaffected and some mycotoxins producing moulds were identified	(Fombong et al., 2017)
Tenebrio molitor L. (mealworm larvae)	Submerging for 10 min in boiling water in a 1/12 (w/w) larvae-water ratio	Small increase in total water content but no significant changes in composition of macronutrients	(Purschke et al., 2017)
Tenebrio molitor L. (live larvae)	Submergingfor 1 min in boiling water or sterilized in cans with brine solution (5% NaCl) for 16 min at 120 °C	4 log cfu/g and 5 log cfu/g reduction in TVC with boiling and sterilization respectively with no observed yeast or mould in either treatment	(Megido et al., 2017)
Archea domesticus (house cricket)	Submerging in boiling water for 4 min or sterilized in cans with brine solution (5% NaCl) for 16 min at 120 °C	4 log cfu/g and 5 log cfu/g reduction in TVC with boiling and sterilization respectively with no observed yeast or mould in either treatment	
Macrotermes spp. (smoked termites)	Submerging in boiling water for 1 min	3 log cfu/g reduction in TVC with boiling and no yeast or mould observed with either treatment	
Cirina gorda(mickwater caterpillar)	Submerging in boiling water for 5 min	3 log cfu/g reduction in TVC and no yeast or mould observed with either treatment	
Tenebrio molitor L. (mealworm)	Submerging in boiling water for 3 min in a 1/10 (w/w) larvae-water ratio, followed by draining for 2 min, and excess water removal with absorbent paper	Increase in water content but no significant changes in composition of macronutrients; decrease in luminosity colour factor and no microbiological data presented	(Azzollini et al., 2016)
Tenebrio molitor (mealworm larvae)	a) Submerging in boiled water for 1 min, 10 min, 5 min followed by 24 hr oven-drying at 55 °C, or 1 min in acid water (pH 4.0) b) Roasting for 10 min whole and crushed larvae	No significant differences in TVC, *Enterobacteriaceae* and or bacterial spores count with different boiling treatments; whereas, with roasting, more *Enterobacteriaceae* were detected both in whole and crushed forms	(Klunder et al., 2012)
Archeta domesticus (cricket)	a) Submerging in boiling water for 5 min b) Stir-frying for 5 min	Higher reductions in TVC with boiling water treatment but no differences in *Enterobacteriaceae* and bacterial spores counts	
Brachytrupus sp. (large cricket)	Submerging in boiling water for 5 or 10 min	No differences found in TVC, *Enterobacteriaceae* or bacterial spores counts with the treatments	
Tenebrio molitor L. (mealworm larvae)	Submerging in boiling water in a 1/10 (w/v) larvae/water ratio for 10, 20, or 40 s, followed by chilling in an ice bath for 30 s	Longer treatments times were more effective; 5 to 6 log cfu/g reduction in TVC with decrease in *Enterobacteriaceae*, yeasts and moulds up to non-detectable ranges; no effect on spores count	(Vandeweyer et al., 2017)

Table 3
Potential technological solutions for extraction of insect macromolecule (hypotheses of the authors).

Valuable compounds	Dry fractionation	Wet fractionation
Whole insect flour	Drying and milling	Blanching followed by drying
Proteins	Fine powder followed by air classification	Pre-treatment (ultrasonic, high pressure, PEF, plasma) followed by enzymatic and chemical routes
Lipids	Dried insect/flour followed by cold press (screw press) – depending on lipid content	Supercritical fluid extraction, solvent extraction
Chitin	Air classification	Chemical extraction processes

reported as a better alternative to linear models that would end with energy recovery or its disposal by incineration and landfilling (IPIFF, 2019). The chemical and physical properties of insect frass are compatible to other commercial fertilisers and it has shown great potential to be upcycled as fertilising product (e.g. soil improver, organic fertiliser, or compost material) (Salomone et al., 2017). For instance, Poveda et al. (2019) reported that the frass produced by *T. molitor* can be potentially used as a biofertiliser in organic farming owing to its nutritional content and associated microbiota which many help in facilitating the absorption of nutrients. Further, a new opportunity for the inclusion of insect frass in the production of biogas has also shown promising results in a cost-efficient and sustainable manner (Bulak et al., 2020). The authors reported a biomethane potential similar to some manures, plant wastes and sewage sludges. Taking advantage of the high fat content of some insect larvae, insect fat has successfully been used for production of biodiesel of similar qualities to oilseeds derived fuel (Wang et al., 2017; Zheng et al., 2013). An ideal insects-for-food and feed production system can be presented in Fig. 3. The figure presents a basic design of mass production of insects using food waste from food production cycle. Rearing of insects for bioconversion, with different steps for producing valuable products and side streams in a holistic way is indicated in the figure.

6. Conclusions and future trends

According to Global Market Insights, the global edible insects market is expected to register significant gains (up to 47%) from 2020 to 2026, owing to increasing protein demand, changing dietary needs and rapid penetration of edible insects preparations in global market place. It has also been projected that edible insects market demand from flour application may witness significant gains during the forecasted timeframe from a value over USD 1.5 billion by 2026 (Ahuja and Mamtani, 2020). However, according to Bakalis et al., 2020 the development of future food chains will require a balance between the current, "global", food supply practices and other, "local", trends and will finally result in "glocal" strategies. Many companies are the front runners in research and development of insect-based proteins for both food and feed. To fully evaluate insect industry, along with the more common criteria such as quality, food safety and expected return on investment, an extensive assessment of the economic, environmental and social sustainability impacts of insect industry would be paramount. In its growing phase, the insect industry has high potential for realising circular bioeconomy strategies in an advanced food production scenarios.

Declaration of Competing Interest

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

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