A review of edible insect industrialization: scales of production and implications for sustainability

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Abstract

Edible insects have emerged in the past decade as a sustainable alternative to agro-industrial production systems and livestock-based diets. Despite the expansion of the market and increases in academic publications, a review of the rapidly changing field of edible insect research has yet to be published. Here we present a comprehensive and systematic review of the research on edible insect industrialization, the mass rearing of insects for human consumption, published in the year 2018. Our review provides an overview of the edible insect industry, as the field becomes more industrialized, and research addresses health, safety, and other concerns of consumers and legislators. This review provides an understanding of the scales of edible insect industrialization from (a) the microbiological level of insect rearing, to (b) the external production factors within rearing facilities, (c) the development of insect products, (d) consumer acceptance of industrially reared insects, and (e) social and moral concerns with the industry. We contextualize reviewed works in relation to earlier and subsequent publications on edible insects, providing a view of the bigger picture as insect-based products are poised to become more widely available to global consumers. Overall, this review provides an overview of the edible insect industry for environmental researchers and policymakers interested in the linkages between food, agriculture, and climate change, as well as recent progress, remaining challenges, and trade-offs of an industry with potential to contribute to more sustainable diets.

1. Introduction

Edible insects are a potential solution to a suite of pressing environmental and human health issues, including climate change, malnutrition, food insecurity, and environmental degradation resulting from agro-industrial production (Davis et al. 2015, van Huis and Oonincx 2017, Godfray et al. 2018, Dickie et al. 2019, van Huis 2020). In 2013, the Food and Agriculture Organization (FAO) of the United Nations published Edible Insects: Future Prospects for Food and Feed Security, which presented a comprehensive analysis of human consumption of insects globally and advocated for edible insects as a viable future food source. Since this landmark report, media and consumer interest in edible insects has increased. The global edible insect market value is estimated to be 406 million USD (2018) and is predicted to increase to over 1.18 billion by 2023 (Statista 2019).

Though the US market is comparatively small (8 million USD), the North American market is predicted to grow more than any other region, an estimated 28% growth by 2023 (Statista 2019). In Europe, edible insect production has been hindered by EU legislation requiring 'novel food' authorization since 2018 (2015 for most EU countries), however, approval is expected to be achieved in 2020, which will have notable impacts on research and broader consumption (Mariod 2020, Boffey 2020).

Peer-reviewed publications on edible insects have also increased substantially in recent years. A Web of Science search reveals an 800% increase, from 14 relevant (non-insecticide related) articles in 2012, to 136 in 2018. A review of the rapidly changing field of edible insect research has yet to be published. Here we present a comprehensive and systematic review of the edible insect industry, based on articles published in the year 2018. Our plan was to review articles
related to the broad theme of ‘edible insects’ to better understand the state of a field generating such academic and popular interest, and gauge its progress in moving toward the promising sustainability and food security goals outlined by the FAO report and current scholars. However, we soon found that most articles published in our sample year were based on applied research aimed at addressing specific stages or scales of the industrial production chain. Our review of 2018 publications thus provides an overview of the edible insect industry at a specific moment, as the field becomes more industrialized and health, safety, and other concerns become more relevant. To better demonstrate the bigger picture, we contextualize the 2018 sample through earlier publications on edible insects, and then, in the discussion, we explain how the emphasis on industrialization in the 2018 sample relates to sustainability and climate change. This review positions 2018 as part of a critical juncture when edible insects became more present in the global food market through applied research and policy shifts, and the field became more industrialized, with some of the same potential drawbacks as other forms of industrial agriculture and livestock production. Overall, this review provides an up-to-date overview of the industry for environmental researchers and policymakers interested in the linkages between food, agriculture, and climate change, as well as the progress and challenges of an industry with potential to contribute to more sustainable diets and food alternatives.

2. Background: edible insect publications and legislation

Past and current research on edible insects recognizes that current food systems, particularly animal agriculture industries, contribute to the climate crisis, and that edible insects are a potentially underutilized food source (e.g. Holt 1885, DeFoliart 1992, Premalatha et al 2011, van Huis Arnold et al 2013). In 2006, the FAO’s report, ‘Livestock’s Long Shadow,’ pointed to the global livestock industry as one of the top three contributors to global environmental degradation, citing, for example, that 26% of the earth’s land is used for livestock grazing and 70% of agricultural land is used for feed production (Steinfeld 2006). The livestock industry also accounts for 8% of human fresh water usage and produces 18% of the planet’s greenhouse gas emissions, more than the total combined emissions from transportation (Steinfeld 2006). It is predicted that global meat demand will double by 2050 (Steinfeld 2006, Davis et al 2015, Godfray et al 2018), due to population growth, but particularly due to agro-industrial expansion and high rates of consumption among affluent consumers and by new consumers in emerging countries (Myers and Kent 2013, Hoelle 2018, Hoelle 2017). In response to the ‘ecological hoofprint’ of the livestock industry (Weiss 2013), researchers and consumers are seeking alternative diets that exert less of an environmental burden, and entomophagy, the consumption of insects, has become an important option among educators, governments, individuals, and NGOs (Prather and Laws 2018, NACIA 2019, Mason et al 2018).

Compared to livestock production, many insects have a high feed-conversion efficiency, can be reared on organic waste, emit few greenhouse gases, and take a small fraction of the feed, water and space required by traditional livestock (van Huis et al 2013, van Huis and Oonincx 2017, Govorushko 2019). With the shift to industrialization, it is difficult to know how sustainable edible insects will be, but some studies have given us an idea (Halloran et al 2017, Wegier et al 2018). In a life cycle assessment conducted by Halloran et al (2017), a mass-reared cricket production site in Thailand was found to have less environmental impact than broiler chicken farms, and they predicted that impact will continue to lessen as cricket farms are further industrialized. Moreover, many edible insects present comparable nutritional benefits to animal-based foods, with high potential for addressing global food and nutrition insecurity (Murefu et al 2019, van Huis 2020, Imathiu 2020). Though macro and micronutrients vary greatly by insect, some species contain as much protein as beef, more iron than spinach, as much vitamin B12 as salmon, all nine amino acids, as well as high calcium, Omega 3 and fiber contents (van Huis et al 2013, Govorushko 2019, Imathiu 2020). Insects have been eaten extensively throughout human existence and are commonly consumed by over 2 billion people today, despite the near absence in the global North (van Huis et al 2013, Lesnik 2019).

Since the FAO report, and especially in the past ten years leading up to 2018, edible insect research has increased substantially, coinciding with a growing acceptance of insect consumption and the appearance of insect food products in the market. Edible insect research prior to 2018 may be best characterized by a focus on disproving the assumptions associated with the insect food aversion. These articles worked to establish credibility for edible insect acceptance in the West, and urged for further research into the feasibility of insects as food. The past two years (2017–2018) of edible insect scholarship presented responses to these research calls and increased studies on the impact of insect consumption on the human body (e.g. digestibility, toxicity, allergenicity, biome impacts), on the environment (e.g. livestock comparison, rearing potential, carbon footprint, policy) and, most notably, on edible insect industrialization practices.

Specific research on edible insects to date includes chitin digestibility (found in the exoskeleton) (Muzzarelli et al 2012), food safety and risk aspects (Belluco et al 2013, Murefu et al 2019), global food security (van Huis et al 2013, Tao and Li 2018), environmental
impact (2011, Henchion et al 2017, Abbasi et al 2015, van Huis and Oonincx 2017), nutrient composition (Rumpold and Schlüter 2013, Raubenheimer and Rothman 2013, Payne et al 2016, Churchward-Venne et al 2017), consumer perceptions (DeFoliart 1999; Hartmann, Siegrist 2017, Mancini et al 2019, Mishyna et al 2020), and insects as animal feed (Sánchez-Muros et al 2014). To date, the only overview of edible insect industrialization is Insects as Sustainable Food Ingredients (Dossey et al 2016), which was published by experts in the field as a guide to industrialized insect production. With the increase in peer-reviewed articles published since this book’s release and the rapidly changing state of the industry, an up-to-date review is clearly needed.

2.1. Legislative framework
Alongside the increase in research, legislation has impacted the science, sale, and public acceptance of insects as food. Though the global market data for edible insects is inconsistent, all reports point to overall edible insect market growth in 2018 (Coherent Market Insights 2020, Statista 2019, Global Market Insights 2020). The US market grew from 6 million in 2017 to 8 million (USD) in 2018 (Global Market Insights 2020). Globally, the edible insect market has increased from 406 million (USD) in 2018, and is estimated to continue to grow to 1.18 billion (USD) by 2023 (Global Market Insights 2020). In edible insect food legislation, 2018 represents a pivotal year. While it marked heightened requirements for insect production, 2018 also marked the transition of production from small-scale and non-vital, to relevant in the global food system and worthy of legislative focus (Vandeweyer et al 2018, Halloran et al 2018, Mariod 2020). In 2015, the EU classified edible insects as ‘novel food,’ which involves an authorization process required for the production of food not commonly consumed in previous years. This classification resulted in a ban of insect products across Europe, however, some European countries (the UK, Netherlands, Belgium, Denmark and Finland) continued to allow the production of edible insects, arguing that animal products do not require novel food authorization. In 2018, however, changes to the novel food requirement specified that all insect producers in the EU must receive the authorization. As of May 2020, many edible insect producers are now in the final stage for complete authorization as ‘novel food’ in the EU and have begun to increase production with anticipation of receiving authorization (Boffey 2020). Upon receipt, production and sale of edible insects will be allowed across Europe, opening the floodgates in the most previously restricted market globally (Boffey 2020). In the US, Canada, New Zealand and Australia, human-grade insects are not classified as ‘novel food’ and their import and sale is permitted (Mariod 2020). In the US, edible insect production must comply with FDA standards and have proper labeling (including allergy risks). In other countries, many to whom insects are a familiar food source, insects are beginning to appear more commonly as packaged foods and mass-production of edible insects is increasing, however, less regulation is present (Mariod 2020). With broad global legislative acceptance set to increase further in the coming months with full EU authorization, the specificities of industrial production and consumption are now at the forefront.

3. Methods
This review focuses on English-language, edible insect industrialization research published in 2018. Here, ‘industrialization’ refers to any mass insect rearing system for the production of human-grade, insect-based foods. We limit the sample of publications to 2018 for a number of reasons. First, 2018 represents a watershed year in edible insect research, with 141 publications. Publications on edible insects have nearly tripled since 2015 and further increased in 2019 to 263 articles (Web of Science). The majority of articles focused on industrialization due to a need for applied research on various elements of the production chain, influenced by aforementioned changes in EU legislation. Limiting the sample to 2018 allows for an in-depth analysis of publications at this moment of transition. This depth is crucial, as this is the first systematic review article on edible insect industrialization, however we also aim to provide an up-to-date view of the industry by contextualizing the analysis with selected publications from 2019 and 2020.

Web of Science was used to generate 141 articles with the topic match of ‘edible insects’ limited to peer-reviewed journal articles published in 2018. After reviewing each article by title, abstract and introduction, the works were coded for topics and further narrowed into subcategories. While the focus of the review was initially limited to human consumption of insects as a way of decreasing the impact of human diets on climate change, the topic was refined to industrialization research based on the results of the literature search. The majority of articles focused on different components of the industrialization process and was oriented to the larger goal of developing a functioning edible insect industry.

Works were excluded from the sample when they diverged from the topic of edible insect industrialization for human consumption, such as insects as animal feed, insects as pests or pollinators, wild foraged insects, food contamination, non-industrially reared insects, insects for waste reduction, health, and non-relevant material (e.g. plant ecologies and bee anatomy). Though many of these topics overlap, this review focuses specifically on the industrialization process, and articles were included only if they applied to human grade rearing practices. After outlying articles were eliminated, the remaining sample consisted
of 66 articles focusing on industrialization research, which were organized according to stage and scale within the mass-rearing process.

4. Results of literature review: edible insect industrialization by scale

We present the literature on edible insect industrialization by organizing it according to scale and stage of the production process, moving from within rearing facilities, to consumption and perception. The scales used in this review extend out from: (1) the microbiology of insect rearing \( (n = 9) \); (2) the external factors impacting production (e.g. temperature, feed) \( (n = 11) \); (3) product development (e.g. enrichment, shelf life) \( (n = 26) \); and (4) consumer acceptance (e.g. taste trials, acceptance surveys) \( (n = 17) \). (5) Additionally, a fifth category was included for three social science articles that considered broader environmental and social elements of edible insect industrialization (table 1). It must be noted that these five stages of industrialized insect rearing both inform and are informed by the legislative framework, a main concern for the mass rearing of insects (Murefu et al 2019). Specificities of rearing and consumption have proven necessary for informing legislation and therefore the sections presented arise from questions and concerns in policymaking, especially with the forthcoming approval of EU production (Murefu et al 2019; Mariod 2020). This review thus presents a perspective of the research on the industrialization process of edible insects, from the insect, to its preparation and perception, and concludes by extending more broadly to discuss the impact of industrial insect rearing on people and environments.

4.1. Microbiology of insect rearing

The consumption of insects is equally a consumption of their microorganisms which are present in diverse ecologies at all stages of the industrial rearing process from live insect to its freezing, processing, storage and consumption. For example, in 2010, cricket paralysis virus (CPV) decimated pet feed cricket farms across the country. As human food-grade cricket farms began to develop in 2014, the first US establishment, Big Cricket Farms, lost six million crickets in 21 d to outbreak of picornavirus, a hurdle similarly faced by other human food-grade cricket farms (Lupo 2015). In many cases, viruses like CPV are incurable and rearing environments cannot be fully decontaminated (Maciel-Vergara and Ros 2017). In 2015, the European Food Safety Authority conducted a risk assessment on insect consumption by animals and humans and concluded that the risks involved in insect rearing are comparable to other animal production systems. They provided detailed methods for good practices and performing the Hazard Analysis Critical Control Points methodology (HACCP), a system for monitoring quality control of microbial risk as well as chemical hazards, allergens and processing hazards (EFSA Scientific Committee 2015, Fraqueza et al 2017).

Understanding the variety and impact of microbiological contexts in the edible insect rearing process is necessary for ensuring food safety and production maintenance, and is therefore a growing area of research (EFSA Scientific Committee 2015). Before we address the sample, a brief explanation of the microbiology of edible insect rearing is useful. Unlike traditional livestock, most microbes found on and in insects are not harmful to humans, but insects are live animals industrially reared in close quarters and are susceptible to harmful microbiological profiles commonly found in other live-animal rearing environments (Marshall et al 2016). Microbiota are divided into two categories: endosymbionts, microorganisms residing within the host insect, and ectosymbionts, microorganisms outside the host insect (Gonzalez-Escobar et al 2018). Endosymbionts aid in breaking down food materials and, in the gut, produce metabolites like amino acids, while ectosymbionts outside the host act as a defense against disease (Gonzalez-Escobar et al 2018). Some microbes are pathogens, which may cause disease in the insect and/or consumer, and may be transmitted among the insect population through production environment, and to humans by handling or consuming (Maciel-Vergara and Ros 2017).

Because of the novelty and microbial complexity of industrial insect rearing for human consumption, this research represented a notable component of the total sample with 9 articles focusing on insect rearing at the microbiological scale. Each article discusses food safety, risk and best rearing practice to eliminate or control for potentially harmful microbes. This sample is further characterized by three factors, (1) the industrial conditions that impact insect microbiota; (2) the survival of pathogens post-product development and (3) methods for decontamination. The research included studies of mealworms (Fasolato et al 2018, Nocciolini et al 2018, Milanovic et al 2018a, 2018b, Osimani et al 2018b), grasshoppers (Milanovic et al 2018b), crickets (Fasolato et al 2018), mole crickets (Fasolato et al 2018, Osimani et al 2018b, 2018a), tropical house crickets (Fasolato et al 2018, Vandeweyer et al 2018), lesser mealworms (Wynants et al 2018), super worms (Nocciolini et al 2018) giant water bugs (Osimani et al 2018b, 2018a), black ants (Osimani et al 2018b), winged termites (Osimani et al 2018b, 2018a), rhino beetles (Osimani et al 2018b, 2018a), silk worm pupae (Fasolato et al 2018, Osimani et al 2018b, 2018a) and black soldier fly larvae (Kashiri et al 2018).

Notably, each article stresses the variability of microbiota. With nearly 2000 species of edible insects and a strong encouragement by the industry to expand industrial rearing from mealworms and crickets to a wider variety of insects, a diversity of
### Table 1. All reviewed articles in the sample organized by category.

| Title                                                                 | Authors           | Journal                          | Category               |
|----------------------------------------------------------------------|------------------|----------------------------------|------------------------|
| Investigation of the Dominant Microbiota in Ready-to-Eat Grasshoppers and Mealworms and Quantification of Carabapenem Resistance Genes by qPCR | Milanovic et al   | Frontiers in Microbiology         | Microbiology           |
| Assessing the Efficiency of Molecular Markers for the Species Identification of Gregarines Isolated from the Mealworm and Super Worm Midgut | Nocciolini et al  | Microorganisms                    | Microbiology           |
| Edible processed insects from e-commerce: Food safety with a focus on the B. cereus group | Fasolato et al    | Food Microbiology                 | Microbiology           |
| Distribution of Transferable Antibiotic Resistance Genes in Laboratory-Reared Edible Mealworms (Tenebrio molitor L.) | Osimani et al     | Frontiers in Microbiology         | Microbiology           |
| Revealing the microbiota of marketed edible insects through PCR-DGGE, metagenomic sequencing and real-time PCR | Osimani et al     | International Journal of Food Microbiology | Microbiology           |
| Microbial Dynamics during Industrial Rearing, Processing, and Storage of Tropical House Crickets (Gryllodes sigillatus) for Human Consumption | Vandeweyer et al  | Applied and Environmental Microbiology | Microbiology           |
| The bacterial biota of laboratory-reared edible mealworms (Tenebrio molitor L.): From feed to frass | Osimani et al     | International Journal of Microbiology | Microbiology           |
| Microbial dynamics during production of lesser mealworms (Alphitobius diaperinus) for human consumption at industrial scale | Wynants et al     | Food Microbiology                 | Microbiology           |
| Use of high hydrostatic pressure to inactivate natural contaminating microorganisms and inoculated E-coli O157:H7 on Hermetia illucens larvae | Kashiri et al     | PLOS One                          | Microbiology           |
| Optimal Temperature for Rearing the Edible Ruspolia differens (Orthoptera: Tettigoniidae) | Lehtovaara et al  | Journal of Economic Entomology     | External Production Factors |
| The fatty acid composition of edible grasshopper Ruspolia differens (Serville) (Orthoptera: Tettigoniidae) feeding on diversifying diets of host plants | Rutaro et al      | Entomological Research            | External Production Factors |
| A new edible cricket species from Africa of the genus Scapsipedus | Tanga et al       | Zootaxa                           | External Production Factors |
| Growing conditions and morphotypes of African palm weevil (Rhynchophorus phoenicis) larvae influence their lipophilic nutrient but not their amino acid compositions | Mba et al         | Journal of Food Composition and Analysis | External Production Factors |
| Role of temperature on growth and metabolic rate in the tenebriod beetles Alphitobius diaperinus and Tenebrio molitor | Bjorge et al      | Journal of Insect Physiology      | External Production Factors |
| Diet acceptance and preference of the edible grasshopper Ruspolia differens (Orthoptera: Tettigoniidae) | Malinga et al     | Applied Entomology and Zoology     | External Production Factors |
| Mixed artificial diets enhance the developmental and reproductive performance of the edible grasshopper, Ruspolia differens (Orthoptera: Tettigoniidae) | Malinga et al     | Applied Entomology and Zoology     | External Production Factors |
| Analysis of Temperature and Humidity Characteristics of Air-Cooled Insect-Rearing Equipment Using Thermoelectric Elements | Sun et al         | Transactions on electrical and electronic materials | External Production Factors |
| Dynamic Effects of Initial pH of Substrate on Biological Growth and Metamorphosis of Black Soldier Fly (Diptera: Stratiomyidae) | Ma et al          | Environmental Entomology          | External Production Factors |
| Utilization of organic residues using heterotrophic microalgae and insects | Pleissner et al   | Waste Management                  | External Production Factors |
| Artificial diets determine fatty acid composition in edible Ruspolia differens (Orthoptera: Tettigoniidae) | Rutaro et al      | Journal of Asia-Pacific Entomology | External Production Factors |
| Title                                                                 | Authors                     | Journal                                          | Category                     |
|----------------------------------------------------------------------|-----------------------------|--------------------------------------------------|------------------------------|
| Identification of antioxidant and anti-inflammatory peptides obtained by simulated gastrointestinal digestion of three edible insects species (Gryllodes sigillatus, Tenebrio molitor, Schistocerca gregaria) | Zielinska *et al*          | *International Journal of Food Science and Technology* | Product Development         |
| Marination and fermentation of yellow mealworm larvae (Tenebrio molitor) | Borremans *et al*           | *Food Control*                                   | Product Development         |
| Development and quality evaluation of crackers enriched with edible insects | Akullo *et al*              | *International Food Research*                    | Product Development         |
| Effect of freezing and drying processes on the molecular traits of edible yellow mealworm | Melis *et al*               | *Innovative Food Science & Emerging Tech*        | Product Development         |
| Bread enriched with cricket powder (Acheta domesticus): A technological, microbiological and nutritional evaluation | Osimani *et al*             | *Innovative Food Science & Emerging Tech*        | Product Development         |
| Structure design of insect-based meat analogs with high-moisture extrusion | Smetana *et al*             | *Journal of Food Engineering*                    | Product Development         |
| Improvement of techno-functional properties of edible insect protein from migratory locust by enzymatic hydrolysis | Purschke *et al*            | *European Food Research and Technology*          | Product Development         |
| Effects of thermal treatments on the colloidal properties, antioxidant capacity and *in-vitro* proteolytic degradation of cricket flour | David-Birman *et al*        | *Food Hydrocolloids*                             | Product Development         |
| Changes in the amino acid profiles and free radical scavenging activities of Tenebrio molitor larvae following enzymatic hydrolysis | Tang *et al*                | *PLOS One*                                       | Product Development         |
| Comparison of functional properties of edible insects and protein preparations thereof | Zielinska *et al*          | *LWT Food Science and Tech*                      | Product Development         |
| Moisture adsorption properties and shelf-life estimation of dried and pulverised edible house cricket Acheta domestica (L.) and black soldier fly larvae Hermetia illucens (L.) | Kamau *et al*               | *Food research International*                    | Product Development         |
| Effect of household cooking techniques on the microbiological load and the nutritional quality of mealworms (Tenebrio molitor L. 1758) | Megido *et al*              | *Food research International*                    | Product Development         |
| On printability, quality and nutritional properties of 3D printed cereal based snacks enriched with edible insects | Severini *et al*            | *Food research International*                    | Product Development         |
| Interfacial and emulsifying properties of mealworm protein at the oil/water interface | Gould *et al*               | *Food Hydrocolloids*                             | Product Development         |
| Potential of Extracted Locusta Migratoria Protein Fractions as Value-Added Ingredients | Clarkson *et al*            | *Insects*                                        | Product Development         |
| Composition of black soldier fly prepupae and systematic approaches for extraction and fractionation of proteins, lipids and chitin | Caligiani *et al*           | *Food Research International*                    | Product Development         |
| Centrifugal fractionation of mealworm larvae (Tenebrio molitor, L.) for protein recovery and concentration | Purschke *et al*            | *LWT-Food Science and Tech*                      | Product Development         |
| Characteristics of fermented seasoning sauces using Tenebrio molitor larvae | Cho *et al*                 | *Innovative Food Science and Emerging Tech*      | Product Development         |
| Effects of formulation and process conditions on microstructure, texture and digestibility of extruded insect-riched snacks | Azzollini *et al*           | *Innovative Food Science and Emerging Tech*      | Product Development         |
| Ultrasonic-assisted Aqueous Extraction and Physicochemical Characterization of Oil from Clanis bilineata | Sun *et al*                 | *Journal of Oleo Science*                        | Product Development         |
| Effect of pre-treatment and drying method on physico-chemical properties and dry fractionation behaviour of mealworm larvae (Tenebrio molitor L.) | Purschke *et al*            | *European Food Research and Tech*                | Product Development         |
| Toxicological safety evaluation of freeze-dried Proctea brevitarsis larva powder | Noh *et al*                 | *Toxicology Reports*                             | Product Development         |
| Title                                                                 | Authors            | Journal                          | Category                  |
|----------------------------------------------------------------------|--------------------|----------------------------------|---------------------------|
| Characteristics, Functional Properties, and Antioxidant Activities of Water-Soluble Proteins Extracted from Grasshoppers, Patanga succincta and Chondracris roseabrunner | Chatsuwan et al    | Journal of Chemistry              | Product Development       |
| Drone brood production in Danish apiaries and its potential for human consumption | Lecoq et al        | Journal of Apicultural Research   | Product Development       |
| Generation of dipeptidyl peptidase IV (DPP-IV) inhibitory peptides during the enzymatic hydrolysis of tropical banded cricket (Gryllodes sigillatus) proteins | Nongnierma et al   | Food & Function                  | Product Development       |
| Biochemical and sensory characteristics of the cricket and mealworm fractions from supercritical carbon dioxide extraction and air classification | Sipponen et al     | European Food Research and Tech   | Product Development       |
| ‘We like insects here’: entomophagy and society in a Zambian village | Stull et al        | Agriculture and Human Values      | Consumer Acceptance       |
| Intentions to consume foods from edible insects and the prospects for transforming the ubiquitous biomass into food | Pambo et al        | Agriculture and Human Values      | Consumer Acceptance       |
| When Utilitarian Claims Backfire: Advertising Content and the Uptake of Insects as Food | Berger et al       | Frontiers in Nutrition            | Consumer Acceptance       |
| Survey on Food Preferences of University Students: from Tradition to New Food Customs? | Conti et al        | Agriculture-Basel                | Consumer Acceptance       |
| Brave, health-conscious, and environmentally friendly: Positive impressions of insect food product consumers | Hartmann et al     | Food Quality and Preference       | Consumer Acceptance       |
| Fostering Strategies to Expand the Consumption of Edible Insects: The Value of a Tripartite Coalition between Academia, Industry, and Government | Mason et al        | Current Development in Nutrition  | Consumer Acceptance       |
| Can edible grasshoppers and silkworm pupae be tasted by humans when prevented to see and smell these insects? | Meyer-Rochow et al | Journal of Asia-Pacific Entomology | Consumer Acceptance       |
| Australian Consumers’ Awareness and Acceptance of Insects as Food | Wilkinson et al    | Insects                          | Consumer Acceptance       |
| Consumption patterns of edible insects in rural and urban areas of Zimbabwe: taste, nutritional value and availability are key elements for keeping the insect eating habit | Manditsera et al   | Food Security                    | Consumer Acceptance       |
| The role of product information on consumer sensory evaluation, expectations, experiences and emotions of cricket-flour-containing buns | Pambo et al        | Food research International       | Consumer Acceptance       |
| Prospects for insects as food in Switzerland: A tobit regression | Schlup and Brunner | Food Quality and Preference       | Consumer Acceptance       |
| Determinants of Edible Insects Consumption Level in Kogi State, Nigeria | Meludu et al       | Journal of Agricultural Extension | Consumer Acceptance       |
| Consumer preferences regarding edible, deep-fried insects in Northern Germany | Grabowski et al    | Berliner und Munchener Tierarztliche Wochenschrift | Consumer Acceptance |
| Consumer acceptance of insects and ideal product attributes | Clarkson et al     | British Food Journal              | Consumer Acceptance       |
| All insects are equal, but some insects are more equal than others | Fischer and Steenbekkers | British Food Journal              | Consumer Acceptance       |
| A qualitative exploration of the factors underlying seniors’ receptiveness to entomophagy | Meyers and Pettigrew | Food Research International       | Consumer Acceptance       |
| Marketing of edible insects in Lake Victoria basin: the case of Uganda and Burundi | Odongo et al       | Journal of Insects as Food and Feed | Consumer Acceptance       |
| ‘Minilivestock’ farming: Who is farming edible insects in Europe and North America? | Wilkie             | Journal of Sociology              | Social Science            |
| Eating for the post-Anthropocene: Alternative proteins and the biopolitics of edibility | Sexton             | Transactions of The Institute of British Geographers | Social Science            |
| Insects as food in the Netherlands: Production networks and the geographies of edibility | House              | GEOForum                         | Social Science            |
microbial profiles is necessary (van Huis et al 2013, Halloran et al 2016, Vandeweyer et al 2018). The differences in rearing practices among different insect types impacts contact with microbes (Fasolato et al 2018). Mealworms, for example, are reared in their substrate and are therefore always in contact with their feed and frass, unlike crickets and silkworms (Fasolato et al 2018).

4.1. Pathogen origins: feed or vertical transmission.
Insects are not known to have naturally occurring microbiota that are harmful to humans, therefore, discovering where pathogens originate was a research question driving publications (Dossey et al 2016, Vandeweyer et al 2018, Osimani et al 2018b). As with other live animal rearing, the production environment is the main concern for controlling pathogens (Dossey et al 2016, Vandeweyer et al 2018). According to this sample, the most notable environmental condition that impacts reared insect microbiota is feed; changes in the insects’ diet represent changes in the gut microbes and, consequently, the rearing environment (Wynants et al 2018, Vandeweyer et al 2018, Milanovic et al 2018a, Osimani et al 2018b). Vandeweyer et al provide the most comprehensive microbial study of industrial insect rearing (tropical house cricket) and performed microbial analyses on the crickets’ feed (before and after it was given), on the crickets live, harvested, frozen, oven-dried and smoked, and on the final product (2018). Vandeweyer et al concluded the highest number of bacteria was found in the crickets’ feed (containing: e.g. Porphyromonadaceae spp., a Bacteroides sp., a Parabacteroides sp., an Erwinia sp., and a Fusobacterium sp.), which was also found within the cricket samples, demonstrating microbial transfer through feed. Yet both Milanovic et al (2018a) and Osimani (2018b) show evidence that potentially harmful microorganisms may instead be passed by vertical transmission, from mother to offspring. Therefore, this sample concludes caution must be taken both in the rearing facility and handling of feed, as well as in processing of insects for safe human consumption.

As evidenced by the sample, ensuring the safe production of edible insects is an important consideration in the further development of the edible insect industry. Unlike other livestock, eating insects involves the consumption of its internal matter, which requires heightened attention to insect feed and production environment, as well as proper preparation by boiling, Blanching, heating, extraction, fermentation and other methods during processing (discussed in section 4.3.2: Increasing Product Safety and Shelf Life). Overall, all articles on microbial makeup published in 2018 concluded edible insects are safe for industrial rearing and human consumption when proper precautions are taken. These precautions determine the external production factors (e.g. temperature, water, feed) within the insect rearing process.

4.2. External production factors
Eleven articles published in 2018 focused on the external production factors, such as feed and temperature, which are crucial to the industrialization process. Here, external production factors are defined as all human-controlled elements within the rearing facility, which affect insect production. In this sample, feed and temperature were considered most relevant, however other external production factors relevant to mass rearing include water, rearing density, rearing area, humidity, cleaning and light. Subjects included manipulating rearing conditions to accelerate production rate, improve nutritional quality, and increase the overall ease and effectiveness of mass rearing. Notably, of the articles in this sample, little research comes from Western industrial practices. Six articles, however, are explicitly concerned with the enhancement of industrial insect rearing in Africa and focus on economic, nutritional and food security development (Lehtovaara et al 2018, Tanga et al 2018, Mba et al 2018, Rutaro et al 2018a, 2018b, Malinga et al 2018a). The limited amount of research on Western-based insect rearing practices may be due to the highly competitive nature of the growing industry and an unwillingness to disseminate new methods for rearing (Wilkie 2018). In Africa, however, this sample shows that dissemination of rearing methods is regarded as necessary to development projects, as evidenced by the funding bodies of some research, including The Improving Livelihood by Increasing Livestock Production in Africa (ILIPA) project (Tanga et al 2018).

Though much of the research focused on insects as a novel food source for enhancing economic development and food security, it was also recognized that edible insects are already a widely accepted food source in many African countries (e.g. Kenya, Uganda). In these contexts, industrial rearing provides an alternative to wild-foraging, a common practice which may place extreme pressure on the environment (van Huis and Oonincx 2017, Malinga et al 2018a). In addition, very few insect species are currently reared and include mainly mealworms, crickets, and black soldier fly larvae. In this research sample (n = 11), however, only 4 articles (Bjørge et al 2018, Ma et al 2018; Sun et al 2018, Pleissner and Rumpold 2018) focused on industrialization of commonly reared species, while 7 articles provided new information for rearing katydids (Lehtovaara et al, Rutaro et al 2018a, 2018b, Malinga et al 2018a, 2018b), a new edible cricket species (Scap- sipedus iclepi Hugel and Tanga) (Tanga et al 2018) and African palm weevil larvae (Mba et al 2018). Industrial rearing according to this sample has the potential to (1) Decrease environmental stress in areas where insects are commonly foraged and consumed; (2)
Increase economic and food security development; (3) Enhance productivity of industrial rearing globally; and (4) Increase industrialization of new insect species. Research on the external production factors influencing development is essential if insects are to be more widely reared.

4.2.1. Temperature.
In this sample, the main external factors in industrial insect rearing were temperature and feed. According to Bjørge et al (2018), of all external factors, temperature is arguably the most important factor affecting metabolism and growth rate, growth efficiency and macronutrient composition. Temperature, according to Lehtovaara et al (2018), ‘determines the survival, development rate, growth rate, and fecundity of insects’ and, with such a large impact on the optimization of production time, efficiency, and quality, understanding how temperature may be controlled is essential. Lehtovaara et al (2018) assessed seven different temperatures for rearing katydids from their nymph to adult stages and concluded the optimum temperature for development time, survival rate and weight gain average was 29 °C. For mealworms, the optimum rearing temperature was concluded to be 31 °C (Bjørge et al, 2018). A study by Sun et al (2018a) analyzed the potential for air-cooled insect rearing equipment to achieve more efficient rearing and to ‘make progress in the insect industry.’ They designed and manufactured environment-control equipment and concluded it is possible to maintain stability for best overall insect performance in rearing.

4.2.2. Feed.
Feed is also an essential component to the achievement of best rearing practice. Often, insects collected in the wild are larger and more nutritious than cultivated insects; therefore insect growing conditions in the wild may inform industrial practices to maximize nutrition (Mba et al 2018, Tanga et al 2018, Rutaro et al 2018a, 2018b, Malinga et al 2018a, 2018b). Rutaro et al (2018a), in an analysis of best feeding practices for rearing katydids, tested four different diet mixtures on the lipid content and fatty acid composition of katydids compared to those collected in the wild. Though there was no noticeable difference in lipid content and weight in relation to the different diets, the composition of fatty acids and proportion of essential fatty acids varied significantly. They concluded diets should be diversified (e.g. rice seed head, finger millet seed head, wheat bran, superfeed chicken egg booster, sorghum seed head) to achieve higher quality essential fatty acid content in reared insects. These findings are further supported by Rutaro et al (2018b) in a study on diversity of artificial diets, and by Malinga et al 2018a, 2018b in a study on diverse feed acceptability. The diversified diet mixtures led to quicker development, greater adult fresh weight and female fecundity (Malinga et al 2018a, 2018b).

In a further analysis of artificial diets in black soldier fly larvae rearing, Ma et al (2018) analyzed the impact of a feed’s pH on insect production, rate of development and longevity by gradually increasing feed pH level. They concluded that larval weight was significantly higher as feed pH increased, at 6.0, 7.0 (control), 8.0, and 10.0. The optimum development time (21.12 d) was achieved at pH 8.0. Black soldier fly larvae are a promising insect for waste management, with potential for human consumption. Pleissner et al (2018) compares black soldier fly larvae to heterotrophic microalgae for waste management and edibility potential. While both significantly converted organic material to biomass and have similar food and feed potentials, Pleissner et al concluded that black soldier fly larvae are more likely to be implemented as a new food source as they are less intensive in an industrialized context and require more simple equipment without sterilization and hydrolysis of organic residues compared to microalgae. The variability of insects requires variability in rearing practices and a varied diet and temperature of 31 °C may not be consistent across species. Transparency among industrial rearing facilities will improve knowledge on best practice and further standardize the safety, nutrition and development of insect consumer products.

4.3. Product development
At the product development level, industrialized insects are transformed into finished consumer products. Though product development and consumer acceptance (section 4.4) are intrinsically linked, with products developed in tandem with consumer experience, this section sample (n = 26) is concerned with the direct adaptation of insect products to improve factors like nutritional profile, shelf-stability and taste, while section 4.4 discusses the ensuing perceptions of these developed products. In this section, topics include analysis of various insect-based products, isolation of nutritional and functional properties, and practices for maintaining shelf stability. By focusing on palatability, taste, nutrition and safety, insect-based products are prepared for increased consumer acceptance.

In this sample, seven articles analyzed insect-based consumer products with the goal of producing ‘diverse, nutritious, convenient and well acceptable insect products’ (Akullo et al 2018). The most common form of industrially reared insect consumption is as a flour or powder, made with dried and ground insects, and added as an ingredient in baked goods. Insect flour was analyzed as an ingredient in crackers (Akullo et al 2018), breads (Osimani et al 2018c) and cereals (Severini et al 2018, Azzollini et al 2018), added to enhance the nutrition of wheat-based foods and create consumer-acceptable insect products. Akullo et al tested for consumer prefer-
ence of different insect types, percentages of insect inclusion, and processing temperatures. They found the preferred cracker of their testing sample was made with 5% winged termite flour, oven dried at 90 °C for 10 min. Similarly, Osimani et al (2018c) concluded wheat bread enriched with cricket-flour at 10% was most preferred and contained a much higher nutritional profile (protein, essential amino acids, fatty acid composition, etc) than non-insect-enriched bread. These benefits were also achieved using 3D cereal-based snack printing technology with mealworm flour (Severini et al 2018). Severini et al concluded 3D printing with insect flour allowed for nutrition enhancement without compromising the structure of the product. Azzollini et al suggests 10% mealworm flour inclusion to maintain structural properties, texture and digestibility with insect fat as the main contributor to changes in microstructure. The functional properties of insect flours can also be further enhanced. Purschke et al (2018b) showed an enzymatic hydrolysis of migratory locust flour (using common enzymes used in the food industry to produce protein hydrolysates, including Alcalase, Flavourzyme, Neutrase, and Lyophilised Papain) improves the solubility, emulsifying, foaming and water/oil-binding properties of flour, and David-Birman et al (2018) demonstrated different baking and processing techniques of cricket flour alters its nutritional and baking properties.

This research sample also included non-wheat based insect products. Cho et al (2018), for example, demonstrated the possibility for a soy sauce-like fermented mealworm-based sauce. Borremans et al (2018) also argued the acceptability, taste and safety of fresh mealworms and other insects can be enhanced by fermentation and marination, which also increases shelf life by at least 7 d. Lecoq et al (2018) suggested bee drone brood, currently discarded by apiaries, should be incorporated into a niche market as a potential food product. They determined that 80 tons of bee larvae biomass could be collected in Denmark annually, which would support a new insect-based market and enhance the sustainability of beekeeping. Additionally, with a recent rise in meat alternative interest, Smetana et al (2018) addressed the possibility for insects to be used in meat substitution innovations. They concluded the best combination for an insect-based meat substitute with the texture, moisture and protein composition similar to meat consists of 40% lesser mealworm biomass and 60% dry soy matter.

4.3.1. Isolation, extraction and fractionation.

Though familiar products enhanced with ground insects have the potential to improve insect food acceptance, much of the research in this sample (n = 14) is concerned with the isolation of nutritional and functional properties of edible insects through extraction and fractionation. These processes have the potential to enhance consumption and bioavailability of nutritional components while further removing the disgust factor of whole or ground insects. The practice of fractionation may also increase the standardization of insect products (Purschke et al 2018a). Insect components can be isolated to enhance particular qualities, for example, antioxidant and anti-inflammatory properties (Tang et al 2018, Chatsuwan et al 2018, Zielinski et al 2018), protein (Gould and Wolf 2018, Clarkson et al 2018, Caligiani et al 2018, Purschke et al 2018a, 2018b, 2018c, Chatsuwan et al 2018, Sipponen et al 2018), lipids (Caligiani et al 2018), chitin (Caligiani et al 2018), and, potentially, glycaemic regulatory properties (Nongioniema et al 2018). In an analysis of protein isolations of three edible insects, crickets, desert locust, and mealworms, crickets were found to have the best functional properties (solubility, foaming, water and oil holding capacity, and emulsion properties) (Zielinski et al 2018b). In a comparison with whey protein, Gould et al found protein extracted from mealworms was functionally comparable to whey protein and required a smaller quantity for the same microstructure and stability. The extraction of protein and other components from edible insects for incorporation into food products can also be extended to insect oil extraction. In a study by Sun et al (2018b) larvae of the velvet hawk moth (Clanis bilinata), a common pest in soybean production and a historically consumed insect in China, was analyzed for potential as a functional edible oil for food and medicine. They concluded the velvet hawk moth larvae oil had high antioxidant properties, lipid content and unsaturated fatty acids and was beneficial in oil form.

4.3.2. Increasing product safety and shelf life.

An integral component to product development and ensuing consumer-acceptance is shelf-stability and product safety. This sample (n = 5) includes methods for increasing safety and longevity of products by various methods. All articles point to heating as the most effective method for insect consumption safety but it is unknown what methods for production are most effective and can be best standardized. At the household level, Megido et al (2018) analyzed the effectiveness of decreasing microbial load, and maintaining nutritional quality and palatability in four methods of cooking mealworms: oven baking, boiling, pan-frying and vacuum cooking. They concluded boiling and vacuum cooking are most efficient for home insect preparation and suggest improved consumer education of home-cooking. Melis et al (2018b) concluded that drying insects on a low temperature for a long period of time has a negative impact on product quality, whereas freezing then high temperature-short time drying better supports the nutritional profile and overall quality. The method of freeze drying also proved safe in a study on
rat consumption of freeze dried white-spotted flower chafer larvae, traditionally used in Asian medicine and suggested as a human food source Noh et al. (2018). As insects have been suggested for nutritional enhancement in humid and tropical areas, the potential changes in shelf life with increased humidity was analyzed by Kamau et al. (2018) in a study on shelf life and moisture absorption of cricket and black soldier fly larvae powders. They found both can have a shelf life of 7 months when kept at 25 °C, dried to 5 g/100 g moisture content with 80 µm thick polyethylene film packaging. In warmer and more humid environments (35 °C), cricket powder was more stable but the shelf life was greatly reduced. Alternative processing and packaging methods are therefore required if these products are to remain stable.

4.4. Consumer acceptance

As stated by Stull et al. (2018), ‘the benefits of edible insects cannot be realized if people do not choose to eat them’. The social acceptability of industrially reared insects is the next step in a scalar analysis of the edible insect industry, but as has been shown so far, this concern permeates each stage of the process and impacts the need for increased edible insect industrialization. Consumer acceptance is variable and impacted by diverse factors including geographic location, legislation, gender, occupation, and socio-economic status (Roma et al. 2020). With over 2000 different types of edible insects, each with a unique flavor profile, acceptance also depends on insect type, processing method and marketing presentation (van Huís et al. 2013, Mishyna et al. 2020). Taste education is also proving a necessary component alongside sensory appeal toward achieving consumer acceptance and is a growing area in current research (Mishyna et al. 2020). As discussed, the industrialization of edible insects is both possible and is emerging globally, yet the social acceptability of insects as food, in contexts both familiar and unfamiliar with insect consumption, remains uncertain. This questioning of the factors influencing consumer acceptance comprises a considerable portion of recent research (n = 17).

4.4.1. Edible insect perception in Africa.

It is widely acknowledged that insect consumption among groups familiar with the practice is decreasing globally due to the spread of Western aversion to insects (Meludu and Onoja 2018). Efforts to reinforce acceptance among local communities familiar with insect consumption is a notable component in the effort to improve nutrition, food security and support more sustainable food practices (Stull et al. 2018). Of the research sample (n = 17), five articles focus on insect consumption in Africa: Zambia (Stull et al. 2018), Kenya (Pambo et al. 2018a, 2018b), Zimbabwe (Manditsera et al. 2018), Nigeria (Meludu and Onoja 2018), Uganda, and Burundi (Odongo et al. 2018). Stull et al. used ethnographic methods to understand collective perceptions of entomophagy in a rural Zambian village and found kinship was not a relevant factor of perception as hypothesized, but that perception was instead related more notably to ‘class, urbanism, gender and age.’ Similarly, Pambo et al. (2018a) in a study on two household types in Kenya (one where insect consumption was common and the other, uncommon), found the main influencers of insect perception were age, gender, size of household and formal education level, and that familiarity with insects as food contributed most to their acceptance. Urban and rural living proximity were also found to considerably influence consumption (Stull et al. 2018, Pambo et al. 2018a, Manditsera et al. 2018). Manditsera et al. found that perceived nutritional value was a more important component for urban participants in Zimbabwe than more rural groups, but that taste was overall the most important factor for both participant groups. In contrast with the Zambian, Kenyan and Zimbabwean studies, in the Victoria basin (Uganda and Burundi), edible insects (mostly katydids) were perceived more positively in urban areas due to successful marketing campaigns (Odongo et al. 2018). Heightened public awareness of benefits and positive taste experiences were regarded as the most effective methods to improve perception and the continued practice of edible insect consumption. Authors also suggest the further development of insect industrialization, which, according to Meludu and Onoja (2018), may be improved by state government-sponsored training.

4.4.2. Edible insect perception of non-familiar consumers.

The factors influencing consumption are similar in contexts where edible insects are an unfamiliar food source, yet the research also presents discrepancies on what factors are most relevant in determining a consumer’s willingness to consume insects (Mancini et al. 2019). Wilkinson et al. points to food neophobia, the reluctance to try new foods, as a main factor influencing perception of edible insects in a study among 820 participants in Australia. However, in a contradicting study, Schlup and Brunner (2018) finds that in Switzerland neophobia is as consistent as other factors, including convenience orientation, perceptions of health benefits and a participant’s gender. According to Conti et al. (2018) in a study of 3556 university students in Italy (18–29 years old), gender was one of the most influential factors of willingness to try, with males reporting a higher preference for all animal protein including insects. Yet their findings also surprisingly show that perceived health benefits (which were concluded as an influential factor by Clarkson et al. (2018a)) did not improve willingness to consume. These findings were consistent with a study by Berger et al. (2018) on the effectiveness of utilitarian marketing (promoting health
and environmental benefits) on 180 German participants from the general population. They concluded that promotion of these long-term benefits of insect consumption actually decreased willingness to consume and that participants instead favored short-term, ‘immediate, hedonic advertisements’ like taste.

With notable discrepancies in findings, understanding variability of consumer bases (Myers and Pettigrew 2018) and of edible insect types (Fischer and Steenbekkers 2018) is therefore necessary. Most notably, the reasons for edible insect consumption often touted by researchers and industry alike are the health and environmental benefits, yet these elements are not consistently effective marketing strategies for increasing consumption and improving edible insect perception. Despite these conclusions, Hartmann et al (2018) found that edible insect consumers were nonetheless perceived positively, as ‘brave, health-conscious, and environmentally friendly’ with high social influence, by 1215 European participants.

Consistently, perceived tastiness was the most relevant factor for consumption and authors suggest that edible insect marketing be accompanied by tastings to introduce consumers to a positive taste experience (Pambo et al 2018b; Grabowski et al 2018). Pambo et al 2018b found that tasting buns with cricket flour lead to an improved experience for consumers in Kenya and these experiences were further enhanced by supplementing tastings with edible insect information. Unsurprisingly, research also concluded that more familiar and processed products like pastas and salty foods (Conti et al 2018), breads (Kennedy et al 2018), biscuits (Wilkinson et al 2018), deep-fried products (Grabowski et al 2018), sweet snacks or drinks (Clarkson et al 2018a) and other products containing insects in flour or paste forms (Meyer-Rochow and Hakko 2018) performed best among consumers. Overall, though marketing strategies are debatable and not cross-culturally consistent, research within this sample shows a positive perception of various edible insects by diverse consumers and a potential for improved consumer education and marketing to enhance edible insect acceptability in the future (Mancini et al 2019, Mishyna et al 2020, Roma et al 2020).

4.5. Social and environmental dimensions of the edible insect industry

As shown, the growth of this industry involves integrated and controlled industrial stages, from microbiology to human perception, but the edible insect industry is also embedded within the global food system and is therefore influenced by broader social factors such as cultural perceptions of food, concerns with the ethics of animals and insects as food, and environmental impacts of food choice. In the other industrialization articles, social and environmental dimensions were often used to justify the importance of increasing human consumption of insects, however, only three articles analyzed these elements with a critical social scientific approach. These works moved beyond discussions of optimization and efficiency and, instead, questioned the industry’s potential impact on the relationships between humans, insects, environments, and technologies. The social science perspectives reviewed in this sample pointed to potential moral and ethical ramifications of industrial production, namely the commodification of life-forms and potential for environmental impacts associated with industrial food production.

In ‘“Minilivestock” farming: Who is farming edible insects in Europe and North America,’ Wilkie (2018) provided an ethnography of EU and North American insect farmers and relies on interviews to demonstrate how the specialized skills of insect rearing are learned and disseminated. Wilkie characterized the edible insect industry in this context as ‘highly competitive and innovative,’ and stated that those who possess knowledge of insects and insect rearing (learned in most cases through past experience of rearing insects for pet feed, or entomological training) are ‘highly sought after by novice farmers and financial investors’ (Wilkie 2018 p 533).

Wilkie described people in the industry as passionate, idealistic, and focused on the potential of edible insect acceptance to alleviate social and environmental issues. Yet, she stated, ‘the extent to which their impassioned visions and practices generate “disruptive innovation” within the conventional livestock sector remains to be seen’ (Wilkie 2018 p 527). In other words, the industrialization of edible insects to alleviate socio-environmental issues is potentially a paradox; by merely inserting insects into an otherwise fossil fuel dependent commodity food chain, the desired social and environmental transformations may not be fully realized (Müller et al 2016). Echoing Buiani (2015), Wilkie positioned insects as ‘the silent majority,’ inhabiting a ‘liminal and “doubly other” status’ which, she argues, necessitates political and ethical consideration by scholars, consumers and industry people if industrialization efforts are to increase (Wilkie 2018 p 534).

In an analysis of alternative proteins and politics of ‘good,’ or ethical, eating, Sexton (2018) further addressed the claims made by the industry that edible insects are environmentally sustainable, hold little animal welfare concern, and are ‘nutritionally superior’ (Sexton 2018 p 587). Sexton showed that the process of shaping the edibility of insects involves not only visceral normalization (e.g. adding insect powder to familiar products), but also the marketing of edible insects as ‘morally charged’ alternatives (e.g. more sustainable, more socially just, and with less concerns for animal welfare) (Sexton 2018 p 596). This marketing strategy targets the relationship between the individual consumer and their food choices as a site for ‘managing societal welfare,’ since food choices often present consumers with the
perceived opportunity to make positive impacts by eating ‘moral’ foods that are considered less harmful to environments, people and animals (Sexton 2018 p587). Sexton’s work supports the industrialization paradox presented above, that despite the perception of edible insects as a moral and sustainable food alternative, these industries have seemingly emerged ‘through the same economic and political mechanisms of power that have been attributed to the very crises they claim to solve’ (Sexton 2018 p597). The professed benefits of increased edible insect consumption seem to necessitate industry growth despite the unknown extent to which a more sustainable food ‘alternative’ is actually achieved.

Similar to Wilkie and Sexton, House (2018) focused on the relationships between producers and consumers within industrial edible insect production networks in the Netherlands, and questioned how success is measured, and how ‘edibility’ is constructed, meaning the process by which insects transition from conceptual categories of ‘non-food’ to ‘food’. House stated that success can be mapped by analyzing relevant actors’ interests. Relevant actors are those involved in the production, supply, and consumption of edible insects, areas that are the focus of most papers in this review, but also the broader ‘socio-material entanglements’, which include farmed insects as more-than-human actors (House 2018 p7).

A focus on the relationships between these elements, therefore, substantiates the need for broader perspectives in scholarly analyses of edible insect industrialization (Lakemond et al 2019). In this review, the literature has been positioned as neatly nested and scalar, from the specificities of production to consumption. This linear model implicitly predicts an eventual transition towards widespread acceptance of edible insects. However, the above perspectives from the social sciences broaden the scope to consider moral, social, and environmental factors that are crucial to evaluating the proposed benefits of edible insects as they become mass-produced commodities or ‘mini-livestock.’ These authors demonstrate the importance of critical social scientific research on emerging frictions, as potential social and environmental benefits are negotiated in relation to the demands of capital-intensive industrialized production.

5. Discussion

In recent years, there has been a dramatic increase in edible insect publications. As this review showed, the majority of articles published in 2018 focused on one of five scales of the industrialization process. In general, we see a concern with increasing food safety and productivity in industrial edible insect operations, guided by an overarching interest in increasing consumer acceptance. While research prior to 2018 often presented edible insects as a somewhat homogenous food source, current research shows the extensive variability of rearing requirements, nutrition profiles, and tastes of different edible insect species. Likewise, present and future insect consumers were also described in greater detail in this research sample, with sociocultural factors (e.g. gender, age, socioeconomic status) found to be influential in determining consumers’ willingness to eat insects in both areas familiar, and unfamiliar with insect consumption. Despite the increase of edible insect industrialization publications, we found that specified information on rearing practices was more widely published when framed as economic or food security ‘development’, but was more closely guarded by Western industry due to increasing competitiveness of the market.

One important finding in this literature review was related to sustainability, specifically the relationship between a) the intent of the industry, and b) the interests of consumers, which is predicted to impact c) industrialization practices. As evidenced by the articles on product development and consumer acceptance, consumers were motivated more by short-term factors like price, taste and availability than environmental sustainability (Berger et al 2018, House 2018). As the edible insect industry continues to find that sustainability is not the main factor influencing insect consumption or acceptance, it is possible continued industrialized insect rearing may forgo some sustainability measures, and the efficacy of insects as a sustainable food alternative could be diminished. Furthermore, the future sustainability impact of insect rearing is largely unknown and there is still an ‘overwhelming lack of knowledge concerning almost every aspect of production: from suitable species, their housing and requirements, and potential for accidental release’ (Berggren et al 2019). As shown, research on this topic has increased substantially, yet a focused, transparent and standardized approach to data gathering continues to be necessary to substantiate sustainability claims. We argue that the applied research dedicated to improving industrial production could benefit from social science and humanities research on the social, moral, and ethical aspects of an industry that has the opportunity to produce on a large scale without the associated environmental impacts of other livestock industries.

Despite challenges to the sustainability of edible insect industrialization, the research and overall global increase in the mass rearing and consumption of insects still indicates potential for a radical change in eating practices. Changes appear to be driven by social and environmental values of producers, governments, and consumers, and aimed at dismantling deeply rooted cultural food aversions in favor of more sustainable and ethical consumption practices. Despite sustainability widely professed as the rationale for increasing edible insect industrialization, the relationship between consumer choice, industrialization
practice, and environmental impact will continue to be an area for research, as evidenced by Halloran et al (2018) and Berggren et al (2019). These topics intersect at the level of legislation, set to change in the EU in 2020, which could facilitate broader global acceptance of insect production and consumption. If edible insects are to be more available, affordable, and, therefore, more widely consumed and accepted as a food source, the scaling-up of industrialization is necessary, but to what extent will these increased industrialization efforts be at the cost of sustainability goals? The fact that increased production and increased acceptance are inextricable raises more questions: Can edible insects remain a ‘sustainable’ alternative if they are industrially reared and inserted into the global food system? What role may localized or home-based edible insect rearing initiatives play in relation to broader industrialization and food security efforts (Dickie et al 2019)? These and other important questions, unique to edible insects as a food source, were beyond the scope of the majority of the articles in this review.

The promise of edible insects as a global food source is coming to fruition through research aimed at increasing efficiency, safety, and acceptance, but the fact that very few articles addressed the social and environmental impacts, and that many were oriented to industrialization by private companies is also cause for reflection. As evidenced by this review, notable future research is necessary to discern the verifiable environmental impact of insect rearing (e.g. energy usage and waste production), alongside measurable evidence for the social impact of edible insects production and consumption. It would be an overgeneralization to position edible insect industrial projects as part and parcel of the same environmentally destructive agro-industrial complex to which many aim to provide an alternative, such as edible insect advocacy groups oriented to food security, and many for-profit edible insect companies operating in a much ‘greener’ mode of production. However, the benefits of edible insect industrialization, with the ability to produce mass quantities of food under strict safety guidelines, and with limited environmental impact compared to other agro-industrial regimes, must remain in focus as the industry expands and insects gain acceptance among consumers.

Data availability statement

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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