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Development of sustainable business models for insect-fed poultry production: opportunities and risks

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REVIEW ARTICLE

Abstract

During the last decade the potential of insects for human nutritional protein is increasingly recognised. Direct consumption of insects contributes to a reduction of the ecological footprint of human food production and is claimed to have health benefits. An alternative is feeding poultry (broilers and layers) with insect-derived protein. This offers several additional advantages, e.g. a more extensive use of (new sources) of organic by-products of food industry for insect production. Implementation of a People-Planet-Profit (PPP) sustainable way of utilising these opportunities requires the development of sustainable business models. Such business models need to be based on the opportunities of insect-derived protein in feeding poultry but should also include the risks associated with insect-derived protein for feeding poultry. This article explores the insect-fed poultry production value chain through an interdisciplinary approach. First, the essential features of this value chain are described. Then, an inventory and classification is made of the main opportunities and risks of this value chain. Finally, the opportunity-risk trade-offs are discussed, as well as their implications for developing sustainable business models. We conclude that for PPP-sustainable business models, management of the asymmetric trade-offs between opportunities and risks related to possible contamination of organic by-products used as substrate for insect production should receive prime attention. Implications for organising the value chain are discussed.

Keywords: insect-based poultry feed, poultry value chain, opportunities and risks, People-Planet-Profit

1. Background and aim

Various factors impact the provision of protein to the rapidly growing human population. The increase in demand for protein is accompanied by initiatives towards a circular production of protein, thus utilising organic waste streams as one of many ways to increase nutrient efficiency (Chia *et al.*, 2019; Godfray *et al.*, 2010; Smetana, 2020; Van Huis, 2013). Alongside these pull factors on protein demand, also push factors regarding protein production face rapid developments such as the emergence of new technologies that enable utilisation of resources which until recently were not considered (Van Huis *et al.*, 2013).

In this regard, the use of insects offers a promising way of providing high-quality protein at large quantities (Parodi *et al.*, 2018; Van Huis, 2020a). Two main directions in which insects as protein source can be utilised are: direct human consumption of insects as food, and indirect use of insects as feed component for livestock (Van Huis *et al.*, 2013). Regarding the latter, particularly poultry production is interesting because of its high feed conversion efficiency (Dörper *et al.*, 2021). Insects may be produced on organic side streams derived from various processes in the food chain.

Feeding poultry with insects that have been produced on organic side streams has several distinct positive attributes to offer in the area of People-Planet-Profit (PPP)[1] sustainability, such as:

- The use of organic waste as main resource for insect production will contribute to a more circular production (Planet) (Bosch *et al.*, 2019; Halloran *et al.*, 2016; Van Huis and Oonincx, 2017).
- The provision of high-quality and protein-rich feed (i.e. insects) to highly efficient resource transformers (i.e. poultry) will considerably improve nutrient efficiency (Planet) (Biasato *et al.*, 2017; Schiavone *et al.*, 2017; Veldkamp and Bosch, 2015).
- The supply of large quantities of high-quality protein will contribute to solving one of the most urgent problems in human nutrition (People) (Parodi *et al.*, 2018).
- The application in both small-scale and large-scale poultry production can improve the economic foundation of people in both emerging and developed countries (People and Profit) (Barragán-Fonseca *et al.*, 2020; Chia *et al.*, 2019; Van Huis, 2020a).

Currently, a lot of monodisciplinary and predominantly technical research is undertaken, focusing on e.g. waste processing, insect production and feed preparation (Van Huis, 2020a; Van Huis *et al.*, 2013). Particularly the application of insect-containing feed in poultry production, i.e. both meat (broiler) and egg (layer) production is considered (Dörper *et al.*, 2021). Yet, ultimately the availability of PPP-sustainable value chains will determine whether the potential for improvement, as indicated above, can indeed be realised. In addition to monodisciplinary research, the development of such value chains requires an inter-disciplinary process, both with regard to knowledge acquisition (i.e. research) and to implementation (i.e. development of business models). For instance, technical problems such as failures in the production process of insect feed, may cause socio-economic risks, such as a drop in demand (Onwezen *et al.*, 2019). Moreover, socio-ethical requirements, e.g. regarding animal welfare, may determine technical demands to the organisation of insect and poultry production.

The occurrence of both technical and economic risks, as well as possibilities to manage these risks, play a crucial role in the development of PPP-sustainable business models. Therefore, a main challenge for PPP-sustainable value chains is to manage these risks in such a way that the utilisation of the opportunity potential is maximised. A first step is to identify the opportunities and the risks along the entire values chain, as well as the connections and inter-relations between them. This will provide a sound basis for the next step, i.e. the identification of potential business models for insect-fed poultry production value chains which are intrinsically robust to risks and at the same time have a high PPP-sustainability profile.

The aim of this paper is to provide a qualitative overview of and insights in the relations between risks, prospects for inter-disciplinary management of these risks and thereby opportunities for future PPP-sustainable business models for value chains utilising organic side streams and insects as a prime resource.

First, the main features of a generic insect-fed egg and broiler value chain will be described, with emphasis on the various processes that occur within these value chains. Subsequently, a qualitative inventory of the main opportunities and risks associated with these processes is provided. This inventory was carried out during an online workshop including all authors, representing various scientific disciplines and societal organisations. Then, a first attempt of confronting general business models with the opportunities and risks has been carried out. This provides first insights into the suitability of particular business models for insect-fed poultry production, as well as legal and institutional requirements. Finally, the main insights are discussed and a future outlook is provided.

[1] Regarding overall sustainability, various terminology exists. In this article the widely spread PPP concept is used, in which: (1) people includes various tangible (e.g. health) and intangible (e.g. social welfare and ethical) values; (2) planet refers to the broad range of ecological aspects (e.g. pollution); and (3) profit includes various economic impacts (for various stakeholders, i.e. ranging from farmers' income via companies' profits to societal profit or loss). Implicitly, PPP includes other concepts such as the RRR-concept (i.e. Reduce, Reuse and Recycle).

2. Description of a generic insect-fed egg and broiler value chain

Overall overview of the value chain

Figure 1 presents a schematic overview of an insect-fed value chain.[2] The chain ranges from utilisation of organic side streams as basic resources (grey) for rearing insects, insect production and the provision of intermediate insect products (all in green), the manufacturing of poultry feed (orange), the use of animals (brown) to produce poultry products for final purchase and consumption (all in pink). Within the value chain, these products can be a resource for the next stage and/or a commodity which can be traded.

Moving down the value chain from one stage (i.e. product) to the next, the first stage either yields a product (e.g. rearing insects results in insect eggs and/or larvae as a product) or is transformed into another product (e.g. intermediate insect products are transformed into poultry feed). Each of these production or transformation steps involves one or more processes (indicated in between two successive stages of the value chain). Single or grouped processes in the value chain are executed by production-involved actor(s) indicated in circles in Figure 1.

[2] Throughout this article the term 'killing' is used when referring to processing insects (including larvae) to intermediate insect products useable in poultry feed mixtures. This is consistent with the IPIFF guidelines (IPIFF, 2019), and similar to terminology used by others such as 'harvesting', 'slaughtering' and 'live larvae provision'.

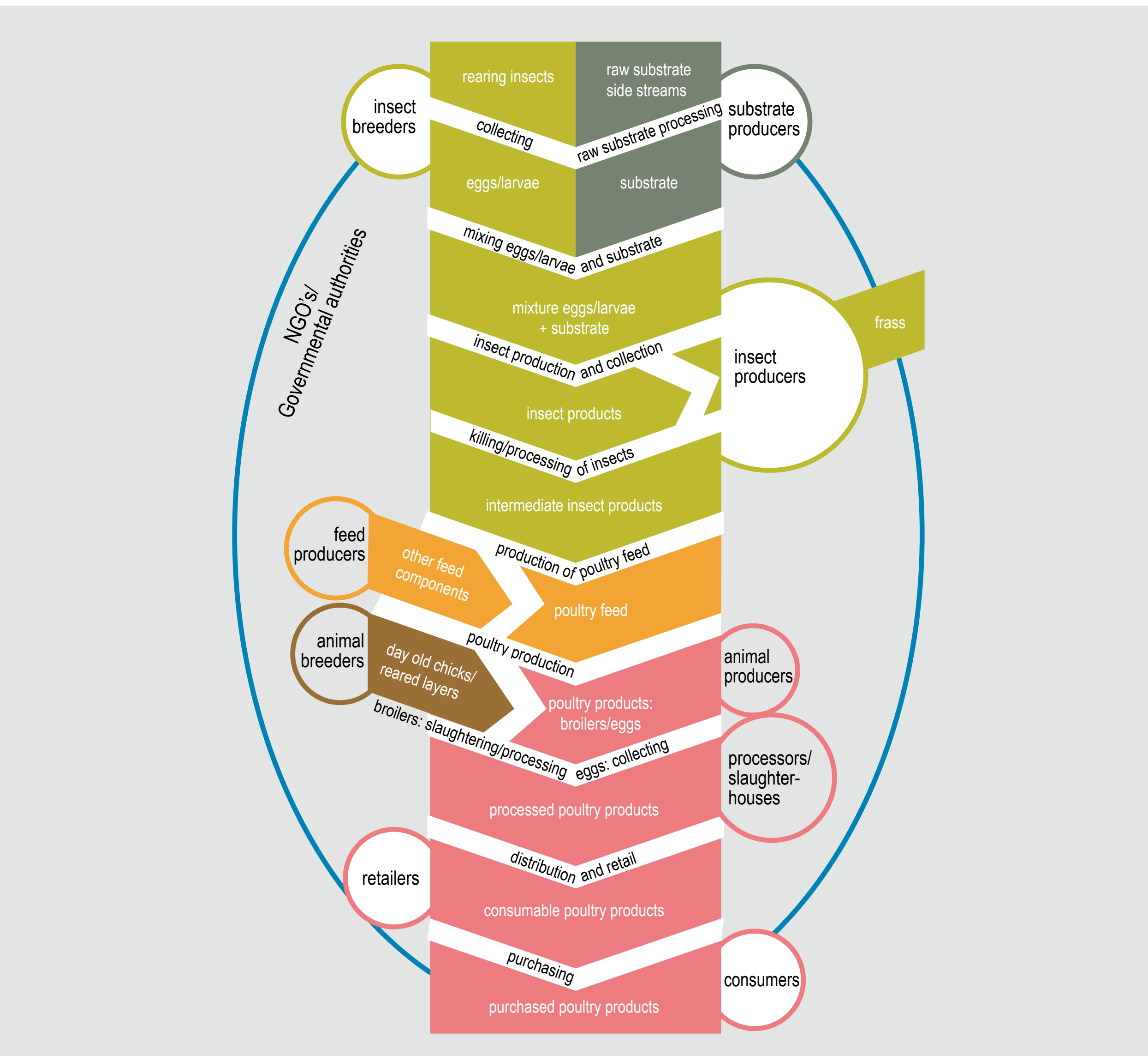

Figure 1. Schematic overview of a generic insect-fed poultry production value chain.

The technical processes in the value chain that are focused on transforming resources into goods for people's benefit are managed by these production-involved actors who make decisions (alone or co-ordinated with other production-involved actors) that keep the value chain running. It is reasonable to assume that independent actors will primarily act to their own benefit and make decisions on production and processes according to their own preferences and risk attitudes. A constraint is that the decision space in which they operate is determined by actors that are not involved in production. Formally, the legal and institutional context within which the value chain as a whole, as well as the individual production-involved actors operate, is the basis for production. These minimal requirements are determined by legal actors (i.e. governments, depicted in the blue ellipse). However, in each society a range of non-governmental organisations (NGOs) are present aiming to influence the legal, beyond legal and institutional context of production. These NGOs can vary from farmer- and producer organisations to consumer and animal welfare organisations. Indirectly, they can change, for instance, legislation by pressuring governments, whereas directly they can take (joint) initiatives towards new production concepts and brands. An example of the latter is how broiler welfare has been improved in the Netherlands (Saatkamp *et al.*, 2019).

A concise, general description of insect-fed poultry production includes the following. Rearing of insects produces eggs, for fly producers, or larvae, which are mixed with substrate produced from raw-substrate and organic side streams (Halloran *et al.*, 2016; Van Huis and Tomberlin, 2017). This mixture provides the basis for the production of insect products (Van Huis, 2020a), as well as frass (excreta of insects) as by-product (Schmitt and De Vries, 2020) that can be used for sustainable crop production (Barragán-Fonseca *et al.*, 2022). Insect products are further processed into intermediate insect products, and, if appropriate, mixed with other feed components. This results in poultry feed. The latter, fed to either broilers (originating from day-old chicks, DOC) or reared layers enables the production of finished broilers and eggs, respectively (Dörper *et al.*, 2021). These are processed (e.g. slaughtered in the case of broilers, or packaged in the case of eggs) and are sold as consumable poultry products to consumers in retail stores (Onwezen *et al.*, 2019).

From Figure 1 it becomes clear that an insect-fed value chain consists of two main parts: (1) the insect part, aimed at production of intermediate insect products resulting in resources for poultry feed; and (2) the poultry production, valorisation and consumption part. Both sub-parts are linked by poultry feed, which may include insect protein. In practice, the poultry production part consists of two distinct and separated value chains, i.e. broiler production for meat and layers for egg production. Hence, two insect-fed value chains should be considered (broilers and eggs), each consisting of two parts (insect and poultry production) with intermediate insect products as the crucial link. Yet, only when strictly necessary, reference to these two poultry products will be made.

The value chain as a whole has the potential to contribute to solving societal problems by introducing efficient protein production and circular production. This originates from the fact that insects, produced on organic side streams, are a protein source for poultry production with its valorisation further down the value chain. Thus, utilisation of the potential depends on collective efforts involving various processes and actors, each having their specific contributions to the total value chain. These processes and associated actors are described in more detail in the subsequent sections.

Essentials of transformation processes and actors involved

In this section the aims and a short description of the process as well as the risks and opportunities are described for each process and associated actor(s) of the value chain. When appropriate (e.g. involving the same actors), processes depicted in Figure 1 are described jointly.

Breeding of insects

In general, breeding of production animals aims to maintain and improve stock populations that are better adapted to mass-production conditions and provide higher quality products (Van Huis and Tomberlin, 2017). Insect breeding differs from traditional livestock breeding in several ways. Due to their small size, insect mass-rearing requires relatively little space, making them ideal for small-scale production facilities, such as individual farmers (Chia *et al.*, 2019; Van Huis and Tomberlin, 2017). Production insects are typically not considered as individuals, but rather at the level of groups, for example in terms of total weight. Social interactions are nevertheless crucial for their breeding. Breeding strategies and housing conditions need to take behavioural interactions between individuals into account, such as mating, aggression and competition, as these will affect the economic profitability of mass rearing (Arvaniti *et al.*, 2019). Some insect species pose specific requirements to their abiotic and biotic environment for mating and oviposition, such as specific light conditions needed during mating (Oonincx *et al.*, 2016). Moreover, as insects are poikilotherm and have daily activity rhythms, environmental rearing conditions need to be carefully controlled, such as temperature and light cycling. Finally, management of microorganisms is an important aspect of insect breeding, both in terms of harmful (e.g. pathogens) as well as beneficial (e.g. probiotics) interactions. Much still needs to be learned about specific conditions for insect breeding in the context of insects for food and feed. The main questions relate to nutritional requirements, best available substrates for the insects, prevention of pests and diseases (Van Huis and Tomberlin, 2017).

Insect breeding includes generating more productive and more resilient genotypes. Domestication of insects may already cause adaptation to artificial rearing conditions, but directed selection for performance may accelerate this process. Care should be taken with such selection procedures as they could come with unwanted correlated responses due to life-history trade-offs, such as between longevity and fecundity (Roff, 2002). Finally, novel genetic and genomic techniques, such as directed genome editing, open up enormous possibilities for improving production methods of insects, as well as for their quality as feed and food. A risk associated with breeding (and production) of genetically altered insects is the risk of escape and establishment in nature.

Production of substrate

The main aim of substrate production is redirection of currently unused organic side streams into resources for insect production to reduce the environmental impact of food production (Parodi *et al.*, 2018). The essentials of this process are: (1) the purchase and/or collection of waste from various sources including crop residues, by-products from the food industry, and restaurant leftovers (for an overview, see: Bosch *et al.*, 2019); (2) processing (i.e. conversion) of these organic streams into a suitable substrate for insects after (pre-)treatment; and (3) marketing/selling the substrate to insect producers. An example of a feed substrate currently used by insect-producing companies is a mixture of brewery by-products (spent grains, yeast), dried distiller's grains and solubles (DDGS) as leftovers of bio-ethanol production, and steamed potato peels from the starch-processing industry. These three organic rest streams are Good Manufacturing Practice+-certified and considered safe for animal feed (European Union Regulation no. 68/2013; European Commission, 2013). The actors involved, i.e. the substrate producers, aim to manage the entire process such that: (1) the costs of transport, collection, processing/conversion/treatment/mixing of organic waste streams are minimised; and (2) profit is maximised.

The three-step process entails various risks and complexities. First, waste batches may be unsuitable due to chemical contamination (environmental pollutants, insecticides, mycotoxins, bacterial toxins) and/or microbial contamination (feed-borne pathogens). This requires regular and rigid sampling and testing whether hazards are below legal safety limits. When limits are exceeded, tracking and tracing should allow the identification of the affected products in next stages of the value chain. Second, processing and transport should ensure that time required is as short as possible from source to insect producers to avoid microbial decay of the substrate and exposure to high temperatures. Finally, under current market and production conditions, demand and hence price is fluctuating.

Using substrate as an (indirect) input for poultry production replaces part of the conventional inputs such as soymeal, wheat or fishmeal. This may have a positive impact on the environment (Planet) provided that the organic side stream is unsuitable for direct use as feed for poultry (e.g. Gold *et al.*, 2018; Lalander *et al.*, 2018).

The main challenges are the chemical and microbial safety of the waste streams and resulting feed substrates. The main risks are limitations of supply of organic waste and/or fluctuations in its availability; these risks are considered to be low, in view of the ever increasing organic volumes of by-products being generated by agriculture, food industry and the growing consumer population. In contrast, low predictability of demand and hence sales price is an important economic risk to take into account.

Production of insects

The insect producers' aim is to generate large quantities of high-quality insects as poultry feed resource (e.g. in terms of protein contents and feed safety) in the most efficient way (i.e. against lowest costs and with highest returns, respectively) (Sorensen *et al.*, 2012; Van Huis and Tomberlin, 2017; Van Lenteren and Tommasini, 1999). Under mass rearing conditions the main determining factors for insect health, welfare and quality include insect density, feed quality and quantity, the presence of pathogens and beneficial microbes, temperature, relative humidity and light regime (Chambers, 1977; Van Lenteren and Tommasini, 1999). These conditions may, directly or indirectly, affect production efficiency, as well as the spread of diseases or the accumulation of noxious waste products. Arguably, a high reproductive output (e.g. number of offspring produced, offspring size and nutritional composition) may be a good indication that the insects are healthy and of good quality. However, reproductive output may not accurately reflect the entire welfare spectrum, as it does not address behaviour, discomfort, pain and distress. Insect health, welfare and quality is challenged when insects are exposed to harmful conditions. Pathogenic microorganisms can cause an infection or may lead to food spoilage through the production of various toxins, both of which can induce severe morbidity and mortality. Crowding may inflict wounding when individuals damage each other (e.g. piercing the cuticle with their mouthparts), and may lead to an accumulation of noxious waste products in the insects' food (e.g. ammonia). Conversely, too low densities or isolation can induce stress or sub-optimal growth and development in insects that aggregate under natural conditions (Wertheim *et al.*, 2005). Suboptimal temperatures or relative humidity can affect physiology and metabolic rates and disrupt homeostasis, in particular membrane and protein integrity, and may induce torpor, sterility and mortality. Moreover, insects have close associations with beneficial microbes (e.g. in their gut), that contribute significantly to their fitness and health and may provide protection against pathogenic microbes (Brinker *et al.*, 2019; Engel and Moran, 2013). The quality and composition of their nutrition may largely affect the composition of microbial communities in their digestive tract. Finally, insects engage in social and sexual interactions, and may have specific requirements for these behaviours, such as particular light conditions. Surprisingly little is known about how to assess welfare of insects, in particular under mass-rearing conditions, and which parameters should be measured to assess their welfare (Van Huis, 2020b). Optimisation of mass-rearing conditions that safeguard insect health, welfare and quality requires a comprehensive assessment of various indicators, such as behaviour, longevity, disease or immune activation, productivity and physiology.

A risk for sustainable production of edible insects is that it does not become acceptable to consumers (People) or profitable for insect producers (Profit). This risk is especially high when insects are produced as food, because food safety and social acceptance are then crucial determinants for the sector. When insects are produced for feed, however, these risks are probably lower. While food safety is still of paramount importance for the production of insects for feed, the processing of insects and including them in poultry feed would considerably reduce the risk of cross-infections or contaminants from insect (food) to humans. Moreover, because insects form a natural part of the diet of poultry in nature, wide societal acceptance is to be expected when insect production is done in a responsible and sustainable way, while respecting insect welfare.

Production of poultry feed

To reduce farmers' dependence on traditional protein sources (e.g. fishmeal and soybean meal), insects and insect products may be a promising, sustainable, protein-rich (partial) alternative for protein components of feed. It is technically feasible to use insects as a sustainable protein-rich feed ingredient in poultry diets (Dörper *et al.*, 2021). Insects can convert low-grade organic side streams into high-quality protein. The chemical composition of organic substrates determines the chemical composition of insect larvae (Lalander *et al.*, 2019; Meneguz *et al.*, 2018; Spranghers *et al.*, 2017). The chemical composition of insect products affects the chemical composition of the final poultry product, i.e. meat and eggs (Gasco *et al.*, 2019). Obviously, insects, like other feed ingredients, should be safe for poultry and their products should be safe for consumption, which is safeguarded by regulations such as those developed by the European Commission (IPIFF, 2019). The main purpose of feed producers is to meet the nutritional requirements of livestock in terms of energy, protein, minerals and vitamins. To provide diversified, localised and sustainable solutions for poultry production, the implementation of insect meal in poultry feed is an important step. In August 2021, new EU legislation provided the legal basis for using insect meal in poultry feed as well as requirements with regard to product and food safety as described in Commission Regulation (EU) 2021/1372 (European Commission, 2021).

In the past decade, research has already focused on the nutritional value of different insect products for poultry, e.g. insect meal and insect oil. In addition to the nutritional value of insect ingredients in poultry feed, the welfare of poultry can also be influenced by the feeding of live insect larvae along the diet. Chickens in outdoor areas collect insects at all life-stages and eat them, which means they are evolutionarily adapted to insects as a natural part of their menu (Józefiak and Engberg, 2015). The potential health-promoting effects of insect products in poultry feeds are an important opportunity for the future. Particular compounds such as chitin, lauric acid, and antimicrobial peptides appear to be capable of modulating the animal microbiota and promoting animal health (Gasco *et al.*, 2018).

Breeding poultry and production of poultry products

In the last 50 years, poultry production has been separated into two different value chains: meat (broilers) and eggs (layers). Poultry breeds used differ regarding adaptation to the specific production aims (i.e. efficiency of meat and egg production, respectively) and the production conditions (i.e. housing and management).

Generally, both value chains are characterised by high intensity and indoors, high feeding density and efficiency, rapid growth, and very large feeding volumes. Alternative systems, which are increasing but still account for less than 5% of the EU production, are less (feed-)intensive but provide positive trade-offs with regard to e.g. poultry welfare (Saatkamp *et al.*, 2019). Feed cost, particularly with regard to protein, is the main factor that affects the economics of broiler production (Gocsik *et al.*, 2013). Hence, breeding and feeding should be directed towards improving the feed conversion rate, i.e. kg feed per produced kg of meat/eggs.

In the last decade, public concern about animal welfare increased, resulting in more robust animals (Saatkamp *et al.*, 2019) and/or improved farm conditions with regard to housing, opportunities for natural behaviour and mutilation practices (Fernyhough *et al.*, 2020). These developments trade-off with feed conversion and thus increase production costs. In this regard, the availability of alternative and potentially cheaper protein sources, such as insect protein, provided they are of comparable value to the currently used fishmeal or soybean meal, could enhance sustainability of poultry production. Various studies show the potential of replacing fishmeal or soybean meal by insect meal to not cause negative effects or even may improve production performance (Gasco *et al.*, 2019) and health (Gasco *et al.*, 2018) of poultry.

Processing of animal products

In industrialised countries, the two poultry value chains, related to meat and eggs, are almost completely separated, from breeding (see previous section) until final consumption.

Eggs are collected at the layer farms, after which they are transported to so-called packing stations. Here, eggs are selected for e.g. quality and weight/size. Two products can be distinguished: table eggs and industrial eggs. The former will, with wholesale and/or retailers as intermediates, reach the final consumers. If specific identification as eggs from insect-fed hens is required (e.g. because of legal requirements) and/or desired (e.g. as higher priced brand), particular care with regard to identification, tracking and tracing should be taken with regard to these table eggs. Hence, prevention of mixing insect-based-eggs with other table eggs is a main challenge during processing, particularly if insect-based branding provides additional value and consequently a higher price.

Industrial eggs are a direct basis for production of various products, ranging from ice cream to cookies and sweets and beyond, or are processed to egg products such as egg powder), which are ingredients for numerous other food and non-food products. Because industrial eggs are a kind of anonymised product, obtaining a price difference with non-insect-based eggs in practice is very unlikely for this product. Therefore, a distinction from non-insect-based eggs makes only sense if legal requirements are installed.

Processing of broilers and final provision to wholesale and retail is much more complicated and includes various stages: transport from farm to slaughterhouse, slaughtering, cutting, packaging of fresh meat or further processing into broiler meat products and final distribution. Moreover, the so-called four-quarter cutting should be considered. Valuable parts (e.g. filet and legs) are sold as recognisable parts, which offer the pursuit for branding and higher prices, but also require proper identification as insect-based broiler meat. Less-valuable parts and offal usually are processed into meat products and hence anonymised. The main challenge (and risk) is to safeguard transparency and origin assurance to the final meat products reaching the consumers. It is not expected that in the near future slaughterhouses and processors completely devoted to insect-based broiler meat will emerge. Hence, logistics should be organised such that guarantees to the final consumers (both legal and beyond legal) can be sustained.

Retail and consumption of products

Processed poultry products are purchased by retailers (including wholesale and purchase organisations) for further distribution for domestic consumption. Here, the main actors are the retailers and consumers at large. Acceptance by the latter (i.e. the products' attributes, including the use of insect feed and its contribution to reducing ecological and other societal concerns) and a willingness to pay are key issues for economic sustainability of the value chain.

The rationale for retail to switch from conventional to insect-fed poultry products is the potential for added value. This is commonly expressed as increased profit for retail, which can be achieved by providing goods that have sufficient value to consumers to pay the requested price. Profit for retail can increase if (1) insect-based poultry products are sold at the same price as conventional products, but their purchase is cheaper, or production chains become more predictable than for conventional poultry or (2) consumers see added value in insect-based poultry products resulting in willingness to pay a price premium for such products.

The majority of consumers is unaware and/or ignorant of the way animals are fed, hence they do not have a pronounced opinion (neither positive nor negative) about animal feeds, including insects (Popoff *et al.*, 2017). Current literature shows mixed evidence on the liking of insects as feed. Some studies report mildly negative attitudes towards using insects as feed (De Faria Domingues *et al.*, 2020), repeatedly related to concern about potential contamination risks that require mitigation and transparent communication (Szendrő *et al.*, 2020; Verbeke *et al.*, 2015). Several studies showed a neutral or slightly positive opinion about insect feed (e.g. Bazoche and Poret, 2020), particularly when insects were fed to livestock which consumers imagine to naturally eat insects (Naranjo-Guevara *et al.*, 2021; Verbeke *et al.*, 2015). A small subgroup of consumers with high sustainability motivations was found to be explicitly positive about insects as feed (Onwezen *et al.*, 2019). This offers the pursuit for a niche market at higher prices but with low sales volumes and specific emphasis on the ecological and social sustainability dimensions. Alternatively, introduction into mainstream markets at limited to no price premium and transparent communication about the use of insects could also be an option.

Legal and institutional aspects, the role of government institutes and NGOs

Legal and institutional requirements

With regard to insect-fed poultry value chains, implementation of concrete and sustainable business models should comply with two legal and institutional issues. First, the use of insects as livestock feed. Initially this was prohibited according to EU-Regulation No 1069/2009 (particularly article 11 1. (b)). Since 17 August 2021, however, the use of processed animal protein derived from farmed insects in feed for poultry and pigs is allowed in the EU as laid down in the Commission Regulation (EU) 2021/1372 (European Commission, 2021).

Secondly, the housing, management and production of mass-reared insects has to be regulated. Currently, insect husbandry is not regulated at EU level. However, given the current rapid developments in the insect-rearing sector, it is expected that the European Commission will implement some basic rules about housing and production of insects similar to regulation for other livestock.

Ethical considerations on insect production for animal feed, beyond legal demands and the role of specific NGOs

Non-governmental organisations (NGOs), particularly consumer and animal welfare oriented NGOs, voice public concerns with regards to various societal and political issues. This generally results in the stipulation of additional efforts or measures, based on ethical considerations. Consequently, these NGOs often aim to achieve requirements that go beyond legal demands. Regarding the emergence of a new insect industry (Van Huis 2021), several moral concerns are raised with respect to sustainability, biodiversity, insect sentience and welfare, and broader animal ethical considerations, e.g. regarding instrumentalisation and genetic modification (Gjerris *et al.*, 2016).

Growing knowledge and understanding of animals has led to clear changes in the public perception and values of animals, causing extensive criticism of intensive and industrial husbandry systems. Similarly, moral concerns have recently extended to invertebrates (Carrere and Mather, 2019; Drinkwater *et al.*, 2019; Mather, 2001; Singer, 2016), thus placing insects into our scope of ethical deliberation. The use of insects as 'mini-livestock' for feed production raises questions similar to those that have previously been asked with regard to conventional livestock (Van Huis, 2020b). For example, do insects undergo subjective states of pain and suffering, and if so, should insects be attributed moral status? Similarly, do insects experience welfare and if so, to what extent is this welfare harmed under mass-rearing conditions? Should we aim for rearing conditions more akin to their natural environment and behaviour in the first place?

Currently, there is no decisive evidence which proves that insects possess the relevant mental capacities demanded by traditional animal ethical theories for the attribution of moral status (Carruthers, 2007; Tiffin, 2016). Yet, there is also no evidence to the contrary, and the absence of proof is not the proof of absence (Gjerris *et al.*, 2015). This knowledge gap potentially justifies employing the precautionary principle (Birch, 2017), because there are indicators for the capacity for subjective experience in some insects (Barron and Klein, 2016), as well as the capacity for pain perception, even as larvae/prepupae (Tracey *et al.*, 2003). In the latter stage, insects are commonly pre-processed and transformed into feed, and methods for stabilisation and killing include freezing or blanching, which are allowed because The European animal welfare Directive 98/58/EC for animal farming does not apply to invertebrates.

However, ethical considerations are not limited to questions of welfare. There are ethical approaches where mental capacities do not play a pivotal role, and thus different philosophical questions emerge. Do insects have an intrinsic value, independent of the purpose (farming or experiments) for which they are used, or with respect to genetic technologies that select for specific traits? Furthermore, industrial and intensive conditions have been confronted with exceeding social criticism and, thus, any new rearing systems may encounter such criticism and resistance as well. This raises the question whether more extensive or local conditions are to be preferred.

For NGOs to determine their standpoint, and whether insect products merit labelling, e.g. for sustainability or animal welfare, more knowledge about insect welfare, monitoring of welfare, animal-oriented design of housing systems and criteria are required. The latter is necessary for NGOs to carefully analyse and evaluate this novel agricultural practice. Leaving these questions unanswered poses a risk at the very first stage (insect breeding) because it could lead to societal resistance and backlash.

Surveillance and auditing

Like all livestock production, both insect and poultry production entails risks with regard to food safety and quality. Emergence of adverse events (such as contaminations) should be detected as soon as possible through surveillance, which can be defined as the process of systematic collection, collation and analysis of data with prompt dissemination to those who need to know, for relevant action to be taken (WHO, 2001). Production of insects and poultry should be subject to (mandatory) legislation (see before) and (voluntary additional) standards of e.g. production concepts (see before). Auditing is done to determine the degree of correspondence between the required and provided protocols and statements, and accepted standards, and communicating the findings to all interested parties.

For a novel value chain, the main uncertainties and challenges are that (mandatory) legislation and (voluntary beyond legal) standards are still under development, especially for insect production and the use of insects as component of poultry feed. Although general legislation regarding production, processing and sales of feed and food is the basis (e.g. the general food law), specific (adaptation of existing) legislation as well as development of new beyond legal standards in the case of concept and brand development are required (see before). Once effective, these should be surveyed and audited. Current and future issues of surveillance and auditing of insect-fed poultry value chains are described below.

3. Inventory of opportunities and risks

In a series of Delphi-based workshops (Dalkey and Helmer, 1963; Rowe and Wright, 2011), an inventory of opportunities for and risks of poultry value chains was carried out, as well as their classification[3]. The final results are described below: first a general qualitative inventory, followed by a semi-quantitative classification. Figure 2 presents a general overview of opportunities and risks. As a frame for its presentation, we use the basic value chain (Figure 1), albeit without actors.

At the left side (green lines) potential opportunities of insect-fed poultry production are listed, whereas the risks are listed on the right side (red lines), with indications for impact on Planet, People and/or Profit. Opportunities and risks can be 'primary', meaning that they have an external or autonomous nature. They also can be 'derived', i.e. being dependent on or triggered by a primary risk (which usually occurs higher-up in the value chain).

Opportunities

Insect and feed production

For the 'upper part' of the value chain, i.e. insect and feed production (Figure 2), the most obvious primary opportunity of insect-fed poultry value chains is the utilisation of new substrates originating from organic side streams for insect production. This ecological opportunity contributes to a circular production, particularly if this concerns side streams and new substrates that are currently not used. Moreover, utilisation of side streams and substrates might result in derived opportunities such as increased nutrient efficiency in insect production, and increased quality of upgraded by-products (green parts). Both cases offer prospects for contributions to ecological and economic sustainability. Furthermore, this way of insect production might stimulate the development of new, more adapted and efficient insect breeds (green part), which offer particularly societal and economic prospects. The ultimate overall (derived) opportunity of the insect production part of the value chain therefore is the increase in the availability of a sustainable protein source for poultry feed production, which has added sustainability value related to all three PPP perspectives.

Poultry production

The (primary and derived) opportunities of the insect production part of the value chain mentioned in the previous section affect the production of intermediate insect products as a sustainable protein source, which is the main input for poultry production. Insects may (partially) replace unsustainable protein sources such as fishmeal and soymeal. Hence, these opportunities may have a downstream impact on the poultry production part of the value chain. The availability of a new high-quality protein source may reduce feed costs (economic opportunity) and improve nutrient/feed efficiency in poultry production (ecological and economic opportunities). Moreover, feeding of live insects to poultry may contribute to improving animal health and welfare (societal and economic opportunities) and providing an increased appreciation and product value by consumers (societal and economic opportunity) (Dörper *et al.*, 2021).

Risks

Insect and feed production

Risks, once emerged, can have considerable downstream impacts along the value chain. First, risks may be triggered by contamination of the organic wastestream or substrate. This contamination can have three different sources: pathogens (which might multiply during the production process downstream the value chain), toxins and chemicals (the latter two might dilute during the production process). All contaminations pose an important planet (i.e. ecological) and people (i.e. the health of humans) risk. Moreover, if not timely eliminated, poultry feed and consequently poultry animals and products can be contaminated, provoking additional social risks. The ultimate outcome of contamination, or even only rumours of it, might be a decrease in consumer trust and acceptance, resulting in demand drops for poultry products, which is a profit (i.e. economic risk) (De Jonge *et al.*, 2007) (see also below).

[3] In the Supplementary material, details on the inventory and classification approach followed are described.

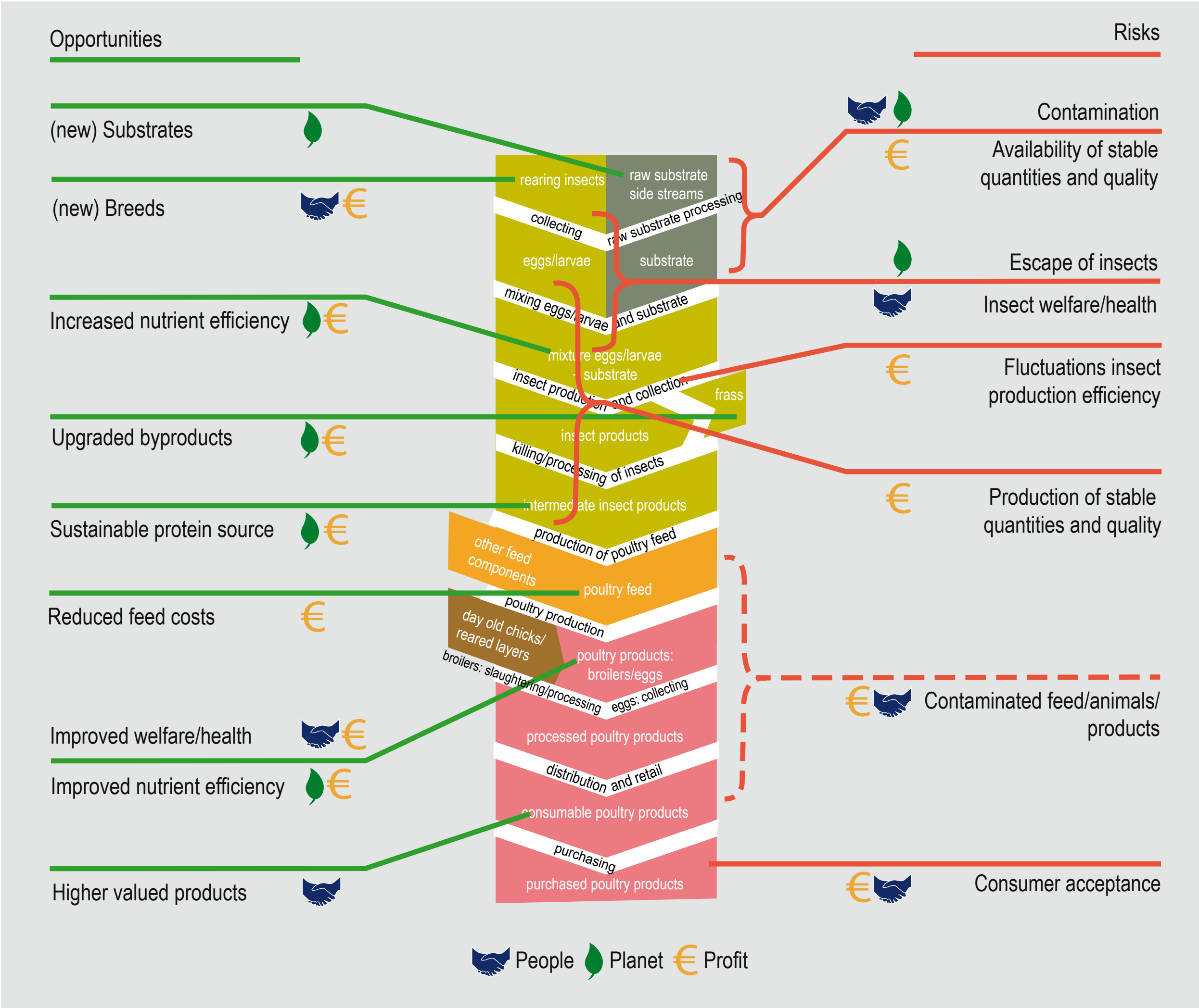

Figure 2. Main opportunities and risks of an insect-fed poultry value chain.

Second, risks are associated with variability in (nutritional) quality and quantity in insect production itself (green parts). This particularly poses an economic (production efficiency) risk for the value chain: variation in the availability of high quality protein for feed production.

Finally, at various stages insects might escape the production process. This may pose an ecological risk such as competition with local species and loss of biodiversity.

Poultry production

No specific insect-feed related primary risks in the poultry production were identified. However, two main derived risks may affect poultry production. First, contamination of feed which causes subsequent contamination of animals and products. The routine risk might be rather low, but incidents of relatively high levels of contamination cannot be ruled out completely. If this occurs, or merely the fear of such an occurrence, consumer acceptance and purchase is at risk. This might be accelerated by media attention, particularly if the insect-fed value chain is still a novel phenomenon. This makes contamination the most important social and economic risk of the value chain.

Second, the risk of volatility in quantity and/or quality of the available insect protein for feed production poses a risk for efficient poultry production as such, both from a technical and economic (cost price) point of view.

Classification of opportunities and risks

The results of the classification of opportunities and risks is presented in Supplementary Table S1.

The main finding appears to be that at the value chain level 'substrate' both the most important opportunity, i.e. the use of new substrates for insect production, as well as the highest risk, i.e. contamination of the substrate on which the insects are reared, occurs.

Furthermore, a broad group of relatively less important derived opportunities were identified, including new insect breeds, increased nutrient efficiency in insect production and the provision of sustainable and cheaper (i.e. reduced feed costs) feed for poultry production, improved poultry health and welfare, nutrient efficiency and higher valued products were classified as being less important.

A group of less important risks included insect health and welfare, fluctuation of quantity and quality of intermediate insect products and the contamination of feed, animals and their products. The availability of substrate and the possibility that insects escape from the production were regarded as having relatively low importance. A special issue is the risk of consumer welfare, particularly public health. In routine situations, i.e. considering only a low likelihood of e.g. contamination, so disregarding a contamination crisis, this was regarded as being less important.

4. Discussion and future outlook

Opportunity-risk trade-offs

When novel insect-fed poultry value chains aim to be PPP-sustainable, their prime objective should be to maximise utilisation of the opportunities while simultaneously minimising the risks they are exposed to, i.e. optimise the trade-off between the identified opportunities and risks (Supplementary Table S1).

The main opportunity-risk trade-off is in the area of utilisation of substrates and the risk of contamination. The main (primary) opportunity of insect-fed poultry value chains appears to be a direct contribution to ecological improvement of the external world: utilisation of current and new organic side streams and substrates. This will contribute to a circular production. This opportunity has a direct link with (primary) risks which have societal and economic implications, i.e. contamination of substrates with pathogens, toxins, etc. Moreover, it is clear that this opportunity-risk trade-off is asymmetrically distributed within the value chain: the ecological opportunities are beneficial for the external world as well as the insect producers, whereas the risks, particularly the derived risks, affect the poultry producers in two ways. First, contamination as such, which may affect poultry and human health, and second, rumours of a possibility of contamination might result in a collapse of demand and/or government-triggered measures to control such food safety crisis such as occurred in the 2017 fipronil crisis in egg production in Europe and Asia (Gallagher, 2017; Lauran *et al.*, 2020). Management of this asymmetric trade-off seems crucial for any PPP-sustainable business model, and requires specific legal and beyond-legal arrangements which should be addressed carefully during the design of the value chain. The latter should include surveillance and auditing to build and foster (consumers') trust in the final products. These issues will be addressed further in the next section.

Second, increased nutrient efficiency by using insects as feed may contribute to a reduced ecological footprint of animal feed production (ecological opportunity), as well as to cheaper poultry feed (economic opportunity). No specific risk trade-offs were identified for this opportunity. However, insect production as such, and particularly on organic side streams, may include the risk of fluctuations in quantities and quality, predominantly as an internal value chain risk. Hence, the trade-off implies the pursuit of ecological and cost price opportunities versus supply uncertainty, which is an economic risk.

Third, regarding the poultry production part of the value chain several opportunities were identified. First, reduced feed costs represent an internal economic opportunity. However, it can provide a comparative advantage over conventional feed, making insect-based production more attractive and (economically) sustainable. The latter can be enhanced by improved nutrient efficiency caused by the insect protein, improved poultry welfare and as a result a higher consumer valuation. Both opportunities provide an economic incentive for poultry producers to join the insect-based value chain. The main risk, not directly associated but derived from others, is contamination followed by an impact on consumer acceptance and demand. This opportunity-risk trade-off will likely influence decision making by the primary producers and the retail.

Finally, with regard to the contamination risks, insect-fed poultry production has an advantage compared to insects as food for humans: poultry could eliminate and/or dilute contaminants, making consumption more safe.

Organisational requirements

As stated, managing the opportunity-risk trade-offs as well as durable and feasible participation of all required individual actors is essential. This has various implications and requirements for the organisation of the value chain, briefly described in this paragraph.

First, because insect-fed poultry production is a novel sector (Van Huis, 2020a), development of a sound legal basis of (minimal) production standards is essential. Recently, new EU legislation has been adopted focused on the use of insect meal in poultry feed (European Commission, 2021). This sets out the requirements with regard to use and product and feed safety. With this adoption, an important threshold for the development of commercial value chains has been taken. Particularly with regard to insect production and feeding to poultry, ethical issues on insect welfare and trade-offs between insect and poultry welfare play a role. Involvement of NGOs in the development of legislation will help to design this legislation in line with both producers' and broad-societal interests. In this way, future societal critique on e.g. insect management and welfare may be prevented.

This legislation will provide a general basis for insect-fed poultry production, particularly mainstream one. However, if the final poultry products are to be sold as specific (niche) brands, additional, beyond-legal production standards will be required on e.g. insect and animal welfare (Saatkamp *et al.*, 2019), quality, regional origin, etc. These standards and concepts can be organised within private or sectoral initiatives, in which all required actors of the value chain should be involved. Moreover, preferably NGOs should be involved as well to increase consumer acceptance, willingness to pay and hence economic sustainability. Recent initiatives on animal welfare in the Netherlands support such a broad participation (Saatkamp *et al.*, 2019).

Second, from (legal and beyond-legal) regulations, technical standards and norms, protocols and procedures, for e.g. production and surveillance, can be derived. These should especially aim to minimise risks of contamination (the main, external risk). However, they cannot be separated from, or should be adapted to, the production system and the value chain features. For instance, surveillance and auditing of large companies or waste streams is cheaper and easier to standardise compared to small ones. Moreover, monitoring of known risks is easier than that of novel risks.

Third, technical production of both insects and poultry, as well as surveillance, must be coordinated to ensure a constant flow of quantities with required quality. This may be achieved through various approaches. One single enterprise, from-waste-to-final-product, clearly offers economics-of-scale, efficiency and food safety prospects. However, this also requires a relatively large and reliable output potential (i.e. consumer demand) to justify the (large) investment and their associated risks. Therefore, a relatively large niche-part (or part of the mainstream) of the consumer market is required. On the other hand, relatively small-scale individual producers of insects are in principle more flexible, but ensuring stable quantities and quality, as well as monitoring the quality of production, is more difficult. A partial consolidation and cooperation, e.g. through contracts between insect and poultry producers, increases the dependency and hence requires trust.

Moreover, two questions are important: which actor(s) take(s) the initiative for an insect-based value chain, and which actor(s) is/are pivotal for this development? Currently, many individual rather un-coordinated initiatives take place. However, for relatively large-scale provision of PPP-sustainable products, part of these initiatives should be coordinated and consolidated to ensure meeting basic requirements with regard to e.g. quality, (in-time) quantity and production standards. Such initiatives could come from (insect) producers (a push initiative); however, this implies that investment risks will have to be taken. On the other hand, retailers could initiate a pull initiative, i.e. create a consumer and, hence, retail demand for insect-fed poultry products. Given the experiences with e.g. animal welfare (Saatkamp *et al.*, 2019), joint initiatives involving respectively triggered by NGOs and retailers have the potential to bring-about such pull-initiatives. Key players in any initiative will be the poultry producers: they have two main feed alternatives (insect-based and non-insect based), hence their opportunity (i.e. feed price) risk (i.e. market and sales) trade-off is of paramount importance.

Fourth, and not the least important: safeguarding the production and final poultry product standards to the consumers is an important requirement. Consequently, monitoring and surveillance, as well as independent, external auditing are crucial instruments in this regard.

Implications for business model development

With regard to business model development, the scale of production seems paramount. Two extremes are imaginable: (1) a highly integrated large-scale production chain, from organic side streams to eggs and meat; and (2) small-scale production systems with on-farm integration of insect production and poultry production.

The advantages of the former are at first sight obvious: scale and hence cost advantages with regard to production efficiency, surveillance and coordination. Such facilities could operate their own brand. However, they require large investments, and hence financial risks, and close ties and hence dependency to retail. Moreover, this is not quite in line with the current organisation of poultry production in some countries like the Netherlands, where primary production largely takes place at individual farms. Finally, although the likelihood of adverse events such as contamination might be low, the impact in case of occurrence is very large. In any case, initiatives in this respect most likely will come from insect producers, i.e. will be push-oriented.

A more fragmented value chain development will be less efficient and requires specific adaptation of surveillance, monitoring and auditing. However, such more small-scale initiatives may originate from demands for niche products. This may transcend the issue of insect-based production, e.g. including regional aspects. Moreover, flexibility and quick adaptation to changing conditions are important aspects. However, small-scale initiatives might not be able to address the main opportunity identified: use of relatively large volumes of waste thereby contributing to a more circular and ecologically efficient way of production.

5. Conclusions and outlook

Insect-fed poultry value chains possess some inherent opportunities to contribute to a circular poultry production, thereby reducing environmental footprints and production costs. Key condition is that the main risk of contamination can be managed. This results in an asymmetric trade-off between upper chain levels opportunities (substrate related) and lower chain levels risks (poultry products and consumer acceptance). Moreover, the former has a rather technical nature, whereas the latter entails both technical (poultry production and food safety) and socio-economic (demand and price) aspects. Any PPP-sustainable business model must be able to manage this crucial trade-off. Inter-disciplinary research covering this trade-off therefore is vital for prudent decision support; the current paper provides a comprehensive framework for such research.

The knowledge base on the options of using insects for feed is developing rapidly (Van Huis, 2020a). However, to date this knowledge is rather fragmented. This article is a first attempt to address qualitatively, in an integral and interdisciplinary way, the prospects and decision making aspects of business model development for insect-fed poultry production. In this sense it provides a basis for interdisciplinary and integrated quantitative research and decision making. Hence, the next step is to address these issues in a quantitative way. Such an approach will include monodisciplinary aspects (e.g. addressing contamination and food safety risks using waste streams for insect and animal production), but eventually should result in an integral and interdisciplinary evaluation of various business models on explicit criteria, i.e. technical risks in production and safety, and economic risks in supply and profit.

Supplementary material

Supplementary material can be found online at https://doi.org/10.3920/JIFF2021.0216

Table S1. Classification of opportunities and risks of insect-fed poultry value chains.

Material and Methods S1. Approach of inventory and classification of opportunities and risks.

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Conflict of 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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