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The feasibility of underutilised biomass streams for the production of insect-based feed ingredients: The case for whisky by-products and Scottish farmed salmon

Georges-Jan J.E. Wehry, David C. Little, Richard W. Newton [*], John Bostock

Institute of Aquaculture, University of Stirling, Stirling, FK9 4LA, UK

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A B S T R A C T

In recent years, insect meal has received considerable attention as an alternative ingredient for aquaculture feeds. When insects are reared on underutilised biomass streams, the resulting meal can potentially offer a reduced environmental impact compared to fishmeal and soybean meal. However, due to legislative restrictions, insects are commonly reared on materials that are also suitable to feed farm animals directly, including farmed fish. This practice compromises both the environmental and economic sustainability of insects as feed. For insect rearing to realise its potential and upcycle organic waste back into the food chain, substrates should thus consist of underutilised biomass. The aim of this study was to identify and assess the feasibility of underutilised biomass streams in Scotland for producing insect-based salmon feed ingredients, specifically defatted meal and oil from black soldier fly (BSF) larvae. Key information was collected on the most important biomass streams in Scotland, including their origin, available volumes, current utilisation, composition, geographic distribution, and legal status for insect rearing. To estimate the performance and body composition of BSF larvae reared on these biomass streams, a literature review was performed. The obtained data were then used to model the feasibility of different biomass streams as substrates for larvae meal and oil production. Based on the results, two whisky by-products are identified as the most promising biomass streams for BSF larvae rearing in Scotland, namely draff and pot ale. Draff is increasingly burned for bioenergy and most pot ale remains unused. It is estimated that 8.500 tonnes of larvae meal and 3.800 tonnes of larvae oil could potentially be produced from the largest geographical concentration of these distillery by-products in Scotland. This would make a considerable contribution to the raw material supply for Scottish salmon feed, whilst generating added value and upcycling otherwise wasted nutrients. However, more studies are required to examine and optimise the actual suitability and feasibility of whisky by-products as a substrate for rearing BSF larvae.

1. Introduction

Scotland is one of the major producers of farmed Atlantic salmon (*Salmo salar*) globally (Shepherd et al., 2017). In 2019, a record production volume of over 200 thousand tonnes was reached, making it the most valuable UK food export (Munro, 2020; Defra, 2020). However, for further development, salmon producers will need to overcome sustainability challenges, particularly related to feed ingredient sourcing (Naylor et al., 2009; Newton and Little, 2018). Historically, fishmeal and fish oil derived from capture fisheries have been the most important raw materials for feed, reflecting the natural diet of salmon, a carnivorous species (Shepherd et al., 2017; Aas et al., 2019). In response to limited availability, rising prices and public debates over their sustainability, these marine ingredients have been progressively substituted by plant-based alternatives over the last two decades (Shepherd et al., 2017; Aas et al., 2019; Naylor et al., 2021). This has enabled the aquaculture sector to drastically reduce its reliance on wild-caught fish (Kok et al., 2020; Shepherd and Jackson, 2013), but the resulting increase in the use of South American soybean meal has led to new concerns over land use and deforestation (Newton and Little, 2018; Malcorps et al., 2019). By 2012, nearly 50% of Scottish salmon feed ingredients, both of marine and terrestrial origin, were sourced from

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Abbreviations: BSF, black soldier fly; LM, larvae meal (defatted); LO, larvae oil; BCR, biomass conversion rate; DM, dry matter; CP, crude protein; CF, crude fat; DDGS, dried distiller grains with solubles; KPI, key performance indicator.

* Corresponding author. University of Stirling, Stirling, FK9 4LA, UK.
E-mail address: richard.newton@stir.ac.uk (R.W. Newton).

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South America, whilst less than 25% originated from the UK (Newton and Little, 2018).

To feed the projected growth of aquaculture sustainably, scientific and commercial efforts have focused on the development of novel feed ingredients (Cottrell et al., 2020). As an alternative source of protein, insect meal is a leading candidate to replace fishmeal (Cottrell et al., 2020; Hua, 2021). Rearing insects for animal feed has received considerable attention, largely due to their ability to grow on organic waste, reflecting increased interests in local production and circular economies (Belghit et al., 2018; Gasco et al., 2020). The larvae of black soldier fly (*Hermetia illucens*, BSF) have been identified as one of the most promising insects for aquaculture feed uses, as their amino acid profile is comparable to that of fishmeal (Belghit et al., 2018; Fisher et al., 2020). Moreover, BSF larvae are not considered a pest species and convert organic substrates more efficiently than other insects (Wang and Shelomi, 2017).

The inclusion of insect-based protein ingredients in fish feeds has been allowed in the EU since 2017 (Van Huis, 2020; Gasco et al., 2020), and in pig and poultry feeds since 2021 (European Commission, 2021). There have been no limitations on the use of insect-based oil ingredients (Gasco et al., 2020). Several feed trials have demonstrated that defatted BSF larvae meal (LM) can either fully or partially replace fishmeal in the diets of both freshwater and seawater stage salmon, without adverse effects on fish performance or product quality (e.g Belghit et al., 2018, 2019a; Fisher et al., 2020; Lock et al., 2016). If successful at a commercial scale, LM could reduce the reliance of salmon aquaculture on fishmeal and soybean meal (Cottrell et al., 2020). Next to LM, the processing of BSF larvae also yields larvae oil (LO), which can be used to replace rapeseed oil, a widely used fish oil substitute in European salmon feed (Belghit et al., 2018, 2019b; Aas et al., 2019). The substrate and faeces left after insect rearing, often referred to as 'frass', can be considered as a marketable by-product. Frass is studied and promoted as a high-quality fertilizer (Schmitt and de Vries, 2020; Quilliam et al., 2020).

Compared to fishmeal and soybean meal, insect meal can only offer a reduced environmental impact when produced from underutilised resources. If materials in the rearing substrate can be directly valorised as animal feed or human food, the environmental benefits of insect meal are compromised (Gasco et al., 2020). According to EU legislation, however, reared insects are classed as terrestrial farm animals. As such, insects can only be reared on authorised feed materials, and pre-consumer agri-food residues are the only waste streams allowed as substrates. These should be of non-animal origin, with some exceptions such as milk and derived products (Bosch et al., 2019; Clark, 2020).

As a results of legislation, insects are commonly reared on materials that are also suitable to feed fish, pigs, or poultry directly (Bosch et al., 2019; Smetana et al., 2019; Gasco et al., 2020). From a food system perspective, using these insects as feed could actually decrease the protein and calorie retention in animal farming systems (Van Zanten et al., 2018; Fry et al., 2018). For insect rearing to realise its potential and upcycle organic waste back into the food chain, substrates should thus consist of underutilised biomass (Bosch et al., 2019; Smetana et al., 2019; Gasco et al., 2020). The aim of this study was to identify and assess the feasibility of underutilised biomass streams in Scotland for producing insect-based salmon feed ingredients, specifically LM and LO from BSF larvae.

2. Methods

To identify the most promising underutilised biomass streams in Scotland for the rearing of BSF larvae, the following steps were undertaken:

i. Classification of Scottish biomass streams according to key characteristics (2.1);
ii. Literature review on the performance and body composition of BSF larvae when reared on substrates containing one or more of the materials identified under step i (2.2);
iii. Techno-economic modelling on the feasibility of Scottish biomass streams as rearing substrates, using the data obtained under step ii (2.3);
iv. Selection of the most promising biomass streams, based on the results of the first three steps (2.4) and;
v. A case study on the potential contribution of BSF larvae rearing to the raw material supply for Scottish salmon feed, using the biomass streams selected under step iv as substrates (2.5).

2.1. *Classification of Scottish biomass steams*

Scottish biomass streams were classified according to their origin, available volumes, current utilisation, composition, geographic distribution, and legal status for insect rearing. To successfully produce LM and LO of consistent quality at commercial volumes, year-round access is needed to affordable, abundant, homogeneous, and legal biomass streams.

2.2. *Literature review on larvae performance and body composition*

There is a growing body of literature on the suitability of different biomass streams as substrates for BSF larvae. The literature review focused on studied substrates that include one or more materials available in Scotland, as listed by the results for section 2.1. Articles published before June 2020 were retrieved from Google Scholar using the search terms 'Black soldier fly' or '*Hermetia illucens*' and 'substrate(s)', and the reference list of each article was checked for relevant studies. The purpose of rearing BSF larvae varied between studies, including feed or biofuel production as well as waste management. As a result, the reported parameters differ among papers. Values for the below mentioned parameters were either taken directly from the articles in the literature review or, when required and possible, calculated from the data presented in these articles.

When rearing BSF larvae for feed production, economic feasibility largely depends on the efficiency of biomass conversion, which is often expressed by the biomass conversion rate (BCR) (Bosch et al., 2019). This widely used metric indicates the fraction of substrate that is converted into larvae biomass. To aid comparison between different substrates, the BCR is commonly calculated on a dry matter (DM) basis as:

$$BCR = lar.out_{(kg\ DM)} \Big/ sub.in_{(kg\ DM)} \tag{1}$$

where $lar.out_{(kg\ DM)}$ and $sub.in_{(kgDM)}$ are the kg DM of the reared larvae and fed substrate, respectively. For this calculation, it is assumed that the initial larvae weight is negligible. Next to the BCR, the substrate reduction rate was also recorded. The substrate reduction rate denotes the share of substrate weight that has been reduced by the larvae culture, an important parameter when rearing BSF larvae for waste management. On a DM basis, the substrate reduction rate can be calculated as:

$$SRR = \left(sub.in_{(kgDM)} - mat.out_{(kgDM)}\right) \Big/ sub.in_{(kgDM)} \tag{2}$$

where SRR is the substrate reduction rate and $mat.out_{(kgDM)}$ represents the kg DM of the leftover material, frass.

If available from the articles, the DM, crude protein (CP) and crude fat (CF) contents of both the substrate and larvae were also recorded or calculated. In cases where a substrate consisted of multiple input materials, the name and inclusion rate of each material were recorded. All the parameters obtained from the literature review are listed in Table 1.

Table 1
Parameters of the techno-economic model, as obtained from the literature review, estimations and calculations. DM: dry matter.

Symbol	Parameter	Units
Literature review		
x_i	name of input material *i*	text
IR_{x_i}	inclusion rate of input material number *i*	decimal fraction
$DM_{substrate}$	DM content of substrate	decimal fraction
$CP_{substrate}$	crude protein content of substrate as %DM	decimal fraction
$CF_{substrate}$	crude fat content of substrate as %DM	decimal fraction
DM_{larvae}	dry matter content of larvae	decimal fraction
CP_{larvae}	crude protein content of larvae as %DM	decimal fraction
CF_{larvae}	crude fat content of larvae as %DM	decimal fraction
BCR	biomass conversion rate	decimal fraction
SRR	substrate reduction rate	decimal fraction
Estimated		
BP_{x_i}	buying price of input material *i*	£/tonne wet weight
SP_{meal}	selling price for larvae meal	£/tonne wet weight
SP_{oil}	selling price for larvae oil	£/tonne wet weight
SP_{frass}	selling price for frass	£/tonne DM
DM_{meal}	dry matter content of larvae meal	decimal fraction
CF_{meal}	crude fat content of larvae meal as %DM	decimal fraction
Calculated		
CR_{meal}	conversion rate for larvae meal	decimal fraction
CR_{oil}	conversion rate for larvae oil	decimal fraction
CR_{frass}	conversion rate for frass	decimal fraction
PV_{meal}	production volume of larvae meal per tonne of substrate DM	kg wet weight
PV_{oil}	production volume of larvae oil per tonne of substrate DM	kg wet weight
PV_{frass}	production volume of frass per tonne of substrate DM	kg DM
CP_{meal}	crude protein content of larvae meal as %DM	decimal fraction
TR	total revenue	£/tonne substrate DM
SC	substrate costs	£/tonne substrate DM
SCM	substrate cost margin	£/tonne substrate DM

2.3. *Techno-economic modelling of substrate feasibility*

A techno-economic model was developed to approximate the feasibility of different substrates. This model used a black-box approach to avoid the need for any assumptions on the operational costs of BSF larvae facilities, which strongly depend on commercial technologies and economies of scale. Instead, only the substrate costs and total revenue were modelled, which were then used to calculate the margin left for operational costs and profits, or the 'substrate cost margin'. To calculate total revenue, it was assumed that all larvae biomass was converted into LM and LO, as these are the main forms in which BSF larvae were trialled in salmon feed. The flow of biomass from raw materials into these final products is illustrated in Fig. 1, distinguishing six production stages and listing the related modelling parameters for each stage.

To model this flow of biomass, the DM and CF contents of LM were estimated, which depend on the larvae processing method (Laroche et al., 2019). Using these estimated values and the values obtained from the literature review, additional parameters were calculated for the conversion of substrate into LM, LO and frass:

$$CR_{meal} = BCR \cdot (1 - (CF_{larvae} - CF_{meal})) \tag{3}$$

$$CR_{oil} = BCR \cdot (CF_{larvae} - CF_{meal}) \tag{4}$$

$$CR_{frass} = 1 - \mathrm{SRR} \tag{5}$$

where CR_{meal}, CR_{oil} and CR_{frass} are the conversion rates of substrate DM into LM, LO and frass DM respectively, whilst CF_{larvae} and CF_{meal} denote the CF contents of the whole larvae and LM respectively as %DM.

To model feasibility, financial parameters were estimated. Firstly, the buying prices were estimated for each input material, including transportation costs. Secondly, the selling prices of LM, LO and frass were estimated. Using these parameter values, the following key performance indicators (KPIs) were calculated per tonne of substrate DM:

- Productivity KPIs: LM, LO and frass production volumes in kg per tonne of substrate DM;
- Financial KPIs: the total revenue, substrate costs and substrate cost margin in pounds sterling (£) per tonne of substrate DM.
- Quality KPI: the CP content of the produced LM as %DM.

The productivity KPIs were calculated as:

$$\mathrm{PV_{meal}} = 1000 \cdot \mathrm{CR_{meal}} \cdot 1/\mathrm{DM_{meal}} \tag{6}$$

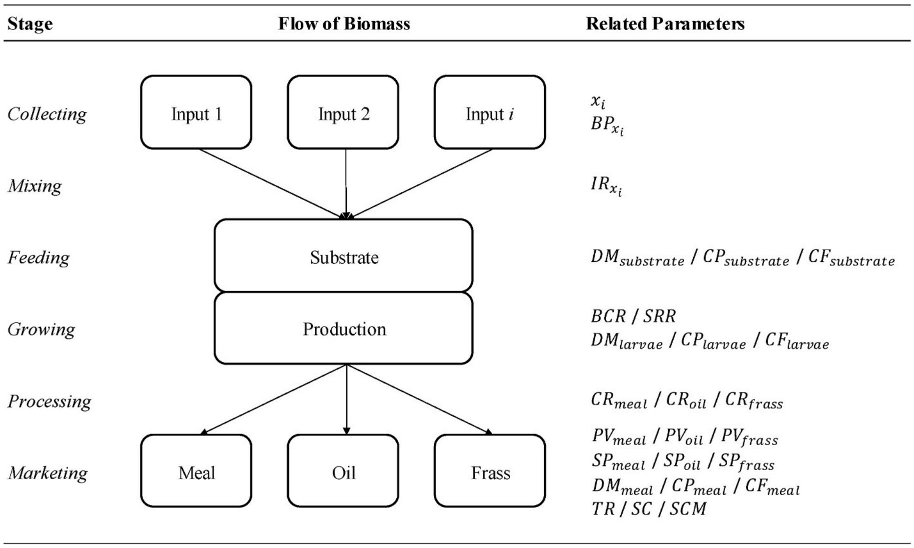

Fig. 1. Flow of biomass through the different production stages of black soldier fly larvae products. Abbreviations are listed in Table 1.

$$\mathrm{PV}_{\mathrm{oil}} = 1000\cdot\mathrm{CR}_{\mathrm{oil}} \tag{7}$$

$$\mathrm{PV}_{\mathrm{frass}} = 1000\cdot\mathrm{CR}_{\mathrm{frass}} \tag{8}$$

where PV_{meal} and PV_{oil} are the production volumes of LM and LO in kg wet weight per tonne of substrate DM, respectively, whilst PV_{frass} is the production volume of frass in kg dry weight per tonne of substrate DM. LM contains a limited amount of moisture, which explains the additional DM conversion in its formula. The moisture content of frass will vary between substrates and rearing systems, which why it is modelled on a DM basis.

The financial KPIs were modelled as:

$$TR = \left(PV_{meal}\cdot SP_{meal} + PV_{oil}\cdot SP_{oil} + PV_{frass}\cdot SP_{frass}\right)/1000 \tag{9}$$

$$SC = 1/DM_{substrate}\cdot\left(IR_{x_1}\cdot BP_{x_1} + IR_{x_2}\cdot BP_{x_2} + \cdots + IR_{x_i}\cdot BP_{x_i}\right) \tag{10}$$

$$SCM = TR - SC \tag{11}$$

where TR, SC and SCM are the total revenue, substrate costs and substrate cost margin per tonne of substrate DM, respectively. SP_{meal} and SP_{oil} are the respective selling prices of LM and LO on a wet weight basis, and SP_{frass} the selling price of frass on a DM basis. $DM_{substrate}$, IR_{x_i} and BP_{x_i} respectively represent the substrate DM content, and the inclusion rate and buying price of substrate input material i.

With LM functioning as a protein source in animal feed, its CP content is an important quality indicator. Although the estimated selling price of LM was not adjusted to its CP content in this model, the CP content was still calculated as a KPI to allow for comparison between meals, using the formula:

$$CP_{meal} = CP_{larvae} / \left(1 - \left(CF_{larvae} - CF_{meal}\right)\right) \tag{12}$$

where CP_{meal} is the CP content of LM as %DM. All the estimated and calculated parameters are listed in Table 1, together with those obtained from the literature review.

2.4. *Selection of the most promising biomass streams*

The results obtained for section 2.3 were used to select the most promising biomass streams in Scotland. The substrate cost margin was identified as the most important KPI for comparing the feasibility of different biomass streams, as it shows the financial room that is available to run a commercial insect rearing facility using a specific substrate. Next to this, the production volumes of LM and LO per tonne of substrate DM were considered, as less productive substrates will result in higher operational costs per tonne of final product. Therefore, at a similar substrate cost margin, less productive substrates were considered less promising. Furthermore, the CP content of the produced LM was considered for comparing the feasibility of different substrates, since LM with a lower CP content is less likely to fetch the estimated selling price. Lastly, to qualify as promising, a biomass stream should also be readily available year-round, underutilised, homogeneous in its nutritional composition, geographically concentrated, and suitable as well as legal for insect farming. To check these criteria, the results obtained for section 2.1 and 2.2 were used.

2.5. *Case study on the most promising biomass streams*

After selecting the most promising biomass streams, the techno-economic model was used to calculate the amounts of LM and LO that could potentially be produced from the volumes currently available. These values were then used to estimate the total value that BSF larvae rearing could add to these promising biomass streams, and what contribution this could make to the supply of raw materials for Scottish salmon feed.

3. Results

3.1. *Scottish biomass streams*

Fig. 2 summarises the main findings on Scottish biomass streams, which were taken from a report by Zero Waste Scotland (2017). As illustrated, the largest volumes of unused biomass streams come from whisky distilleries. The production of whisky yields two significant by-products, namely draff and pot ale. The former consists of moist grains from the first stage of production and the latter is a liquid residue from distillation. Historically, these by-products have been utilised as high-protein animal feeds. Draff can be fed to livestock directly, whereas pot ale needs to go through an evaporation process to concentrate its solids into an animal feed called 'pot ale syrup' (Bell et al., 2019; Zero Waste Scotland, 2015). To improve their handling, draff and pot ale syrup can be combined and heat-processed to produce a solid feed ingredient called 'dried distiller grains with solubles' (DDGS) (Zero Waste Scotland, 2015; Bell et al., 2019). In recent years, increasing amounts of whisky by-products are utilised to generate bioenergy (Bell et al., 2019; Gandy and Hinton, 2018). This development is driven by the government's carbon reduction targets and related incentives (Leinonen et al., 2018; Bell et al., 2019). Draff can be combusted in combined heat and power plants, whilst anaerobic digestion can convert pot ale into biogas for uses in transportation or heat and electricity generation (e.g. O'Shea et al., 2020; Kang et al., 2020; Jackson et al., 2020). At present, all draff is valorised, either as animal feed or through energy recovery, whilst the majority of pot ale is still discharged (Zero Waste Scotland, 2015, 2017). However, the Scottish Whisky Association aims to generate 80% of its primary energy requirements through anaerobic digestion by 2050, so higher utilisation rates for pot ale can be expected (Jackson et al., 2020). In addition to draff and pot ale, malt distilleries also yield spent lees, which is a liquid residue from the second distillation stage. Its properties are similar to pot ale, but more dilute (Zero Waste Scotland, 2015, 2017). More information on whisky by-products and their current valorisation routes is provided in Fig. 3.

The early stages in beer breweries are comparable to those in whisky distilleries and therefore produce by-products similar to draff and pot ale called 'spent grains' and 'spent yeast' (Zero Waste Scotland, 2015). The nutritional compositions of whisky and beer by-products can be found in Table 2. Whilst most biomass streams in Scotland are geographically dispersed, which could lead to high collection costs, whisky and beer production and the availability of their by-products are spatially concentrated (Zero Waste Scotland, 2015). This concentration has already encouraged value addition, such as a combined heat and power plant in the Speyside area, which valorises around 20% of all draff and pot ale in the country from surrounding distilleries (White et al., 2016, 2020). Likewise, 60% of all spent grains and spent yeast in Scotland is produced in a single brewery (Zero Waste Scotland, 2017).

3.2. *Larvae performance and body composition*

Fig. 4 lists all the substrates from the literature review that included one or more of the materials present in Scotland, as reported by Zero Waste Scotland (2017) and summarised in section 3.1. BSF larvae have been studied on DDGS, spent grains and spent yeast, whilst no literature was found on draff and pot ale as substrates. Other studied substrates include animal manures, sewage sludge, by-products from food processing, and organic waste from other sources such as restaurants. The obtained BCR values for each substrate are illustrated, together with the CP and CF contents of the resulting larvae biomass. In the techno-economic model, these values served as inputs to calculate the conversion of substrate into larvae biomass, and the conversion of larvae biomass into LM and LO. The exact composition of each substrate can be found in Table S1, Supplementary Materials, which also lists all the parameter values as reported or calculated from data provided in the literature. No values were obtained for the substrate reduction rate, as it

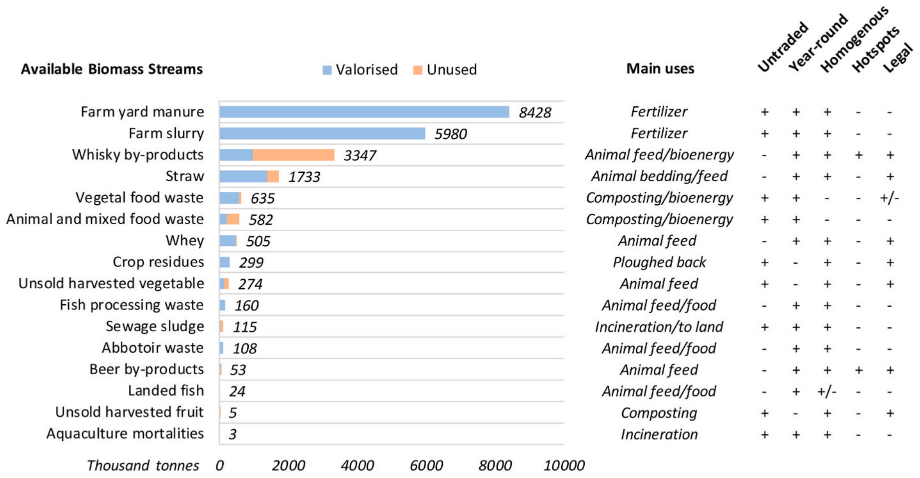

Fig. 2. Summary of the main findings on Scottish biomass streams. Annual volumes, shares valorised and main uses from Zero Waste Scotland (2017; personal communications). Untraded: '+' when there is no established market value for a biomass stream. Year-round: '+' when a biomass stream is available year-round. Homogeneous: '+' when the nutritional composition of a biomass stream can be expected to be homogeneous. Hotspots: '+' when more than 20% of the total available volume is concentrated at a single facility. Legal: '+' when a biomass stream is legally allowed as a substrate for insects used in animal feed (Bosch et al., 2019; Clark, 2020).

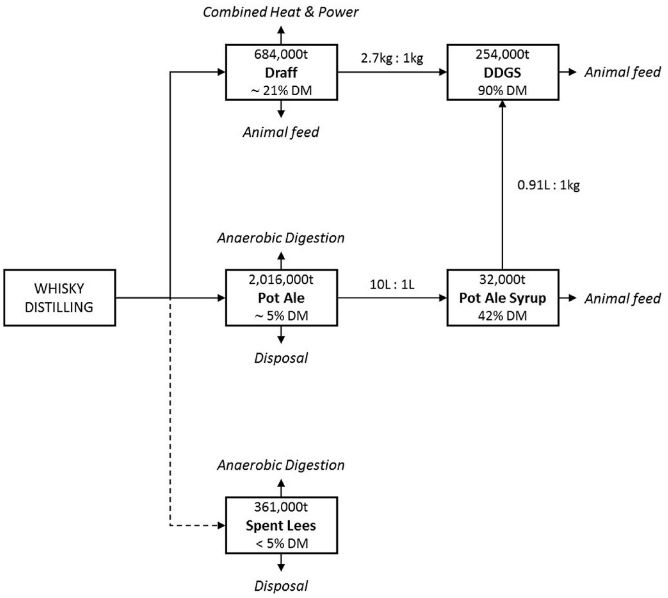

Fig. 3. Overview of the volumes of different by-products from whisky distilleries, and the conversion rates of pot ale evaporated into pot ale syrup, and draff and pot ale syrup into dried distiller grains with solubles (DDGS). Data obtained from Zero Waste Scotland (2015; 2017).

Table 2
Nutritional characteristics of distillery and brewery by-products. Values are taken from KW Alternative Feeds (2020).

	DDGS (wheat)	Pot ale syrup	Draff	Spent grains	Spent yeast
DM %	90	42	18–24	20–26	15
CP (%DM)	28	30–35	22–24	24	41.7
CF (%DM)	8	1	9	7	2
High in yeast		✓			✓

Abbreviations: DM, dry matter; CP, crude protein; CF, crude fat; DDSG, dried distiller grains with solubles.

data on frass was not reported consistently.

The literature review yielded additional insights on the value of substrates for rearing BSF larvae. Firstly, it became clear that very little is known about the actual nutrient requirements of BSF larvae, making it challenging to estimate the suitability of substrates without testing them (Tschirner and Simon, 2015). Secondly, it was found that BSF larvae can barely degrade lignin, limiting their ability to break down materials rich in cellulose, like straws and crop residues (Liu et al., 2018). This may explain the relatively low BCR values observed for most dairy manures, which often contain forage fibres from the cow diet (Barragan-Fonseca et al., 2017). Thirdly, it was found that BSF larvae may depend on microbial populations in their food (Barragan-Fonseca et al., 2017; Richard et al., 2019). Therefore, it is thought that heat-dried substrates may be less suitable for BSF larvae, which could explain the low BCR values observed for DDGS and the dried manures tested by Oonincx et al. (2015a) (Bosch et al., 2019). Substrates with spent yeast, on the other hand, resulted in some of the highest BCR values. Lastly, it was found that BSF larvae lack biting and chewing mouthparts and thus prefer liquid slurries as food (Lalander et al., 2019). Indeed, multiple papers reported relatively dry input materials, such as poultry starter feed or (freeze-) dried biomass, which were mixed with water to increase the moisture content of the substrate (Tschirner and Simon, 2015; Oonincx et al., 2015a, 2015b). According to Barragan-Fonseca et al. (2017), the optimal moisture content of the substrate lies between 52 and 70 percent. However, some articles in the literature review reported higher values (see Supplementary Materials, Table S1). Next to drying, the addition of water, and mixing, other forms of pre-treatment were reported for the various substrates. These include grease extraction (Zheng et al., 2012) and cutting or grinding (Oonincx et al., 2015b; Barragán-Fonseca et al., 2018; Lalander et al., 2019). Some substrates were also stored frozen before experimental use (Liu et al., 2018; Lalander et al., 2019).

3.3. Substrate feasibility

Fig. 5 presents the KPIs per tonne of substrate DM for different substrates from the literature review. To calculate the production volumes of LM and LO from any substrate, both the BCR and CF content of the reared larvae need to be available. This was not the case for all substrates from the literature review, which is why only some substrates were modelled. To calculate the CP content of LM, the CP content of the reared larvae biomass needs to be available, which was not always the case. The revenue calculations exclude any possible income from frass, since only a few articles reported data on its volume or composition, and still little is known about its potential value. For substrate cost calculations, estimates had to be made on the buying prices of all individual input materials. When data on these prices were unavailable, estimates were made on the costs per tonne of substrate DM. These estimates, including their justification and related sources, can be found in the Supplementary Materials, Table S2. Table S4 in the Supplementary Materials show the calculated parameters, the underlying estimates and

Fig. 4. Overview of the substrates selected from the literature review, with the reported or calculated biomass conversion rate (BCR) as a percentage in blue, and larvae crude protein (CP) and crude fat (CF) contents as percentages dry matter (DM) in orange and green, respectively. “Mixed” indicates additional material was part of the substrate. Exact substrate compositions are available in the Supplementary Materials, Table S1. DDGS: dried distiller grains with solubles.* NB: two overlapping data pionts for Larvae CP and CF. References: A, Li et al. (2011); B, Diener et al. (2011); C, Zheng et al. (2012); D, Tschirner and Simon (2015); E, Oonincx et al. (2015b); F, Oonincx et al. (2015a); G, Nyakeri et al. (2017); H, Rehman et al. (2017b); I, Rehman et al. (2017a); J, Liu et al. (2018): K, Barragán-Fonseca et al. (2018); L, Lalander et al. (2019). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

data from the literature review.

With regard to the estimated selling prices of LM and LO, it should be noted that the present study focuses on the use of LM and LO as substitutes for fishmeal and rapeseed oil in salmon feeds. In terms of nutritional value, LM and LO offer amino acid profiles and energy levels, respectively, that are comparable to those of their conventional counterparts. Therefore, it is assumed that the long-term selling prices of these alternatives will, at best, equal those of fishmeal and rapeseed oil. As such, the price of Danish fishmeal, with a relatively low CP content of 64 percent, is taken as a reference price for LM (£1200 per tonne, free on board, North Germany (Hammersmith Marketing LTD, 2020)), and the price of rapeseed oil as a reference price for LO (£720 per tonne, free on board, Rotterdam (IndexMundi, 2020)). However, it should be stated that, at the time of writing (2021), insect-based ingredients sell at considerably higher prices than the ingredients they aim to replace. Currently, LM prices range from £3000–4700 per tonne (De Jong and Nikolik, 2021). This is expected to come down to £1300–2150 by 2030, when the global market for insect-based ingredients is believed to reach maturity (De Jong and Nikolik, 2021).

Commonly, benefits related to sustainability and animal performance are claimed to justify a price premium for LM, such as a decreased dependency on wild-caught fish and improved gut health (De Jong and Nikolik, 2021; Gasco et al., 2020). In reality, these claims have a debatable scientific foundation. All other things equal, replacing fishmeal with LM requires increased levels of fish oil inclusion, as LM lacks the essential fatty acids that fishmeal provides (Ewald et al., 2020; Belghit et al., 2018, 2019a; Fisher et al., 2020; Lock et al., 2016). Since more fish biomass is required to produce fish oil compared to fishmeal, replacing fishmeal with LM alone could lead to an increased Forage Fish Dependency Ratio (Cottrell et al., 2020; Kok et al., 2020). Therefore, an

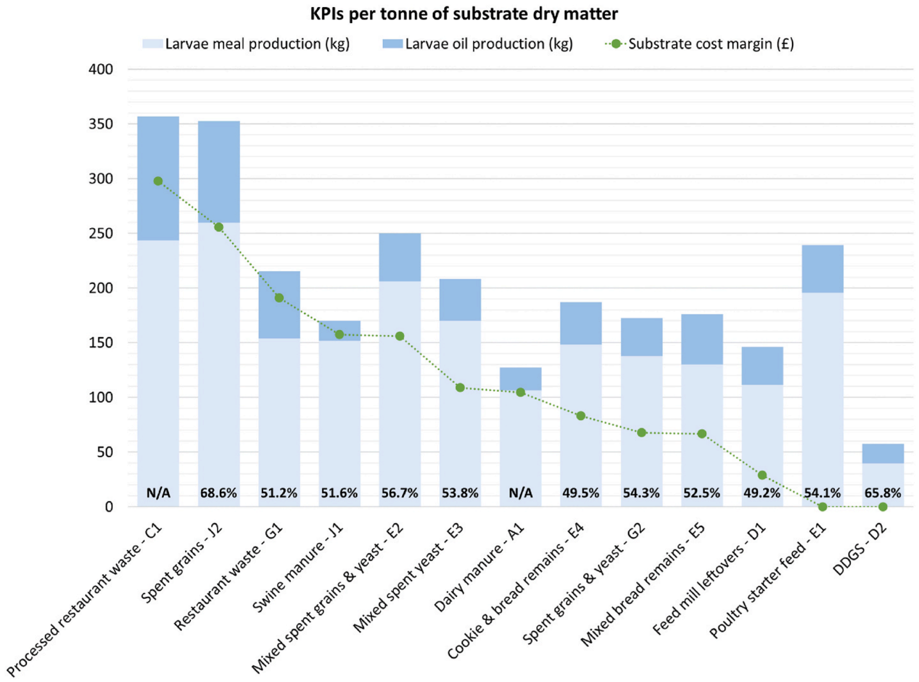

Fig. 5. Key performance indicators (KPIs) for the modelled substrates. % denotes the crude protein content of the produced larvae meal as percentage dry matter. "Mixed" indicates additional material was part of the substrate. Table S4, Supplementary Materials, list the exact composition for each substrate, as well as the related parameters. DDGS: dried distiller grains with solubles. References: A, Li et al. (2011); C, Zheng et al. (2012); D, Tschirner and Simon (2015); E, Oonincx et al. (2015b); G, Nyakeri et al. (2017); J, Liu et al. (2017).

alternative source of essential fatty acids, such as algal oil, is needed to decrease the marine dependency of feeds when using LM (Cottrell et al., 2020). The nutritional benefits of LM are not superior to fishmeal either. Fishmeal is still widely referred to as the "gold standard" for protein ingredients in aquaculture feeds, which is an oversimplified way of stressing its high nutritional value and applicability (Turchini et al., 2019). Taking all this into account, it could even be argued that the estimated price of LM in this study, which equals that of fishmeal, already includes a price premium.

3.4. Promising biomass streams

As explained in section 2.4, the substrate cost margin was the most important KPI for comparing the feasibility of different substrates. Fig. 5 shows that some of the highest substrate cost margins are found for processed and unprocessed restaurant waste. Processed restaurant waste yields the largest volume of LM and LO combined, making it a productive biomass stream. However, the CP content of the LM from unprocessed restaurant waste is relatively low, whilst that of processed restaurant waste is unavailable. The consistency of the LM and LO quality can also be expected to vary, at least for unprocessed restaurant waste, as this substrate is unlikely to be homogeneous in its composition. For these reasons, a lower selling price should be expected for the larvae-based ingredients from restaurant waste, which is not accounted for in the model. Furthermore, restaurant waste is currently banned as a substrate for rearing insects as feed. Manures, which are also banned, yield relatively average substrate cost margins, with low or unavailable LM CP contents as well. In addition to that, manures are among the least productive substrates that have been modelled. Therefore, relatively high operational costs per tonne of LM and LO should be expected for these substrates, making them less attractive compared to restaurant waste.

Of the legal substrates, DDGS and poultry starter feed leave no substrate costs margin, meaning that the costs of these substrates exceed the revenue that can be obtained from the resulting feed ingredients. This is not surprising, considering that these materials are already utlised as animal feed. Of the modelled substrates, those containing spent grains and/or spent yeast seem the most promising, resulting in some of the highest substrate cost margins. Furthermore, these substrates are among the most productive and yield LMs with relatively high CP contents. This may be explained by the nutritional value that the yeast in these materials offers to BSF larvae.

In Scotland, however, only limited volumes of these beer by-products are available, most of which are already valorised as animal feed. Therefore, spent grains and yeast do not meet the criteria of being underutilised, as set out in section 3.4. Draff and pot ale, on the other, are currently underutilised, as the burning of draff for bioenergy destroys its valuable nutrients and most pot ale is still being discarded. According to the EU food waste hierarchy, governments should prioritise the recycling of these materials into human food or animal feed, above other valorisation routes such as composting and energy recovery (Salemdeeb et al., 2017). Due to carbon reduction incentives from the Scottish government, however, bioenergy became a more profitable valorisation route to distilleries than animal feed (Bell et al., 2019).

Insect rearing may present an even more profitable way to utilise draff and pot ale. Although not tested as a substrate, the performance and body composition of BSF larvae reared on these whisky by-products may be reasonably similar to larvae reared on beer by-products. This is because the nutritional characteristics of draff and pot ale (syrup) match those of spent grains and spent yeast, respectively. Particularly the high levels of yeast fragments in pot ale (syrup) and spent yeast may result in a favourable BSF larvae performance and body composition. Taking into account their available volumes and current valorisation routes, draff and pot ale are identified as the most promising substrate materials in Scotland.

3.5. Case study

The techno-economic model is used to estimate the feasibility of draff and pot ale syrup when mixed together as a substrate for BSF larvae, focusing on the largest geographical concentration of these materials. Roughly 20% of all draff and pot ale arisings are collected at a combined heat and power plant in Speyside. Annually, this plant burns 130,000t of draff for energy, and 430,000t of pot ale is converted into 44,000t of syrup for animal feed (White et al., 2016). Draff and pot ale syrup are thus available in a ratio of 3:1. Previously, this combined heat and power plant produced DDGS, which is a dried and concentrated mixture of approximately 75% draff and 25% pot ale syrup (Zero Waste

Scotland, 2015; White et al., 2016).

Fig. 6 compares the different valorisation routes for the draff and pot ale syrup at this plant. The first bar shows the volumes available, and their combined market value as animal feed is plotted on a red dashed line. This market value serves as a conservative estimate for the costs of these raw materials when used for DDGS production or BSF larvae rearing. The second bar shows the volume of DDGS that could be produced from the available draff and pot ale syrup, together with the revenue this would generate. The remaining bars show the estimated amounts of insect products that could be produced from these raw materials under two different scenarios. Draff mixed with pot ale syrup has not been tested as a substrate for BSF larvae, but DDGS has. To model the feasibility of an unprocessed DDGS equivalent of 3:1 draff and pot ale syrup, the parameter values observed for DDGS were used (substrate D2 from Figs. 4 and 5). The resulting productivity and revenue are illustrated by the third bar in Fig. 5, the 'LOW' scenario. This serves as a conservative scenario, as the BCR observed for DDGS was among some of the lowest observed in the literature review. This can be explained by the involved heat-drying process, destroying microbiota and limiting its suitability for BSF larvae. Therefore, the higher BCR value observed for mixed spent grains and yeast (substrate E2 from Figs. 4 and 5) was used as an alternative estimate for the productivity of unprocessed draff and pot ale syrup. The resulting LM and LO production as well as total revenue are presented by the fourth bar in Fig. 6, the 'HIGH' scenario, serving as an optimistic scenario. Again, any potential income from frass sales is left out of the total revenue in Fig. 6, since there is not enough information available on the quantity, quality and value of frass coming from these substrates.

This case study shows that as much as 8.5 thousand tonnes of LM and 3.8 thousand tonnes of LO could be produced from the volumes of draff and pot ale syrup currently available at the combined heat and power plant in Speyside. To put this in perspective: the total fishmeal consumption by Scottish salmon aquaculture was around 55.3 thousand tonnes in 2014, and the total rapeseed oil consumption around 33.2 thousand tonnes (Shepherd et al., 2017). If the obtained LM and LO would sell for the same prices as fishmeal and rapeseed oil, a total revenue of £13 million could be achieved. This is £2.2 million more than the production of DDGS would yield, and £6.1 million more than the value of the available draff and pot ale syrup as direct animal feed.

4. Discussion

4.1. Limitations of the data

Substrate quality is among the most important factors that affect the growth and survival of BSF larvae and thus their efficiency of biomass conversion (Barragan-Fonseca et al., 2017). Indeed, the observed BCR values vary considerably between the substrates of the reviewed studies. However, these studies have used markedly different test procedures, some of which have been reported as sub-optimal for obtaining an optimal BCR (Bosch et al., 2019). Notable examples of such differences between studies are related to the initial larvae weight, larvae density and feeding ration, all of which can affect the BCR. For calculating the BCR, it was assumed that the initial larvae weights in trials were negligible, because culture commonly starts from the microscopic newly hatched larvae. Many of the cited studies did not report the initial larvae weight, whereas others reported weights that were high enough to impact the BCR value. Larvae density and feeding ration can also affect the BCR, as an increased availability of substrate per larva positively affects growth, but negatively affects the efficiency of substrate reduction (Barragan-Fonseca et al., 2017). As a result of these varying procedures, the available data do not allow further analysis of the most important substrate characteristics affecting the BCR. For these reasons, caution is advised when interpreting the reported BCR values as representative for the tested substrates (Bosch et al., 2019). Moreover, trial and error in commercial settings may lead to a better larvae performance than reported for the experimental setups in literature.

The quality of substrates is also known to affect the body composition of BSF larvae, with variations observed in CP and even more so in CF. The amino acid profile of BSF larvae, on the other hand, has been shown to remain relatively constant between substrates (Barragan-Fonseca et al., 2017). This variation in body composition is apparent from the collected data, with CP ranging between 36 and 50% and CF between 18 and 39%. Unfortunately, the differing test procedures also hamper any overall conclusions about the effect of substrate characteristics on the body composition of BSF larvae. In this respect, one notable point of difference between studies is the time of harvest, since the body composition of larvae also depends on their life stage (Barragan-Fonseca et al., 2017). Thus again, caution is advised when interpreting the reported larvae CP and CF as representative for the tested substrate. Furthermore, there are large differences in the larvae development time between studies and substrates.

As mentioned in the results, modelling the production and quality of frass was complicated by the different ways in which articles report

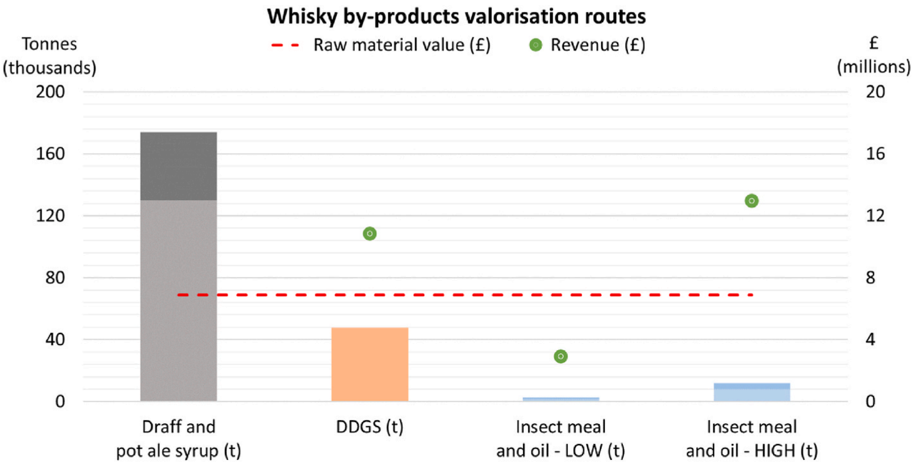

Fig. 6. Different valorisation routes for whisky by-products. Light and dark grey bars: available volumes of respectively draff and pot ale syrup. Orange bar: potential volume of dried distiller grains with solubles (DDGS). Light and dark blue bars: potential volumes of respectively larvae meal and oil, under the two different scenarios (LOW and HIGH). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

material reduction. Efforts are made to standardise studies on insect rearing, including procedures for the reporting of findings on bioconversion and body composition (Bosch et al., 2020). Compared to conventional animal farming, insect rearing is a relatively unexplored field, and scientists are only beginning to understand the factors that underly efficient bioconversion by insects. As academic and commercial research in the area progresses, improvements can be expected, for example by optimising substrate characteristics, genetic strain selection and understanding the role of substrate microbiota (Bosch et al., 2019, 2020).

4.2. *Limitations of the model*

Some key assumptions should be taken into consideration when interpreting the results of this study. Most importantly, it was assumed that LM could be sold at the same price as Danish fishmeal. This assumption is based on the nutritional value that LM would offer in the formulation of salmon diets. If the commercial reality turns out to be different, with the price of LM either substantially higher or lower than the price of fishmeal, the model results would also turn out considerably more favourable or unfavourable in terms of substrate feasibility. When comparing the potential revenues between the substrates illustrated in Fig. 5, it should be noted that the selling prices of the different LM's are not adjusted to their estimated CP contents, whereas in reality, this would likely result in different values.

Another important model assumption is that all larvae biomass is converted into a defatted LM and a LO. In reality, BSF larvae producers may choose to sell certain proportions of their biomass in different forms and for different purposes than aquafeeds. For example, major BSF larvae facilities also sells biomass as live larvae and full-fat meal for applications in poultry and pet feeding. Such producer choices can be modelled for, but this was outside the scope of the present study, which focused on BSF larvae for the use in salmon feed. The varying time it can take for larvae to develop on different substrates is also not accounted for in the model. However, longer development times could lead to higher operational costs, affecting the feasibility of substrates. Similarly, the life cycle stage at the time of harvest has implications for the operational costs. When reaching the so-called 'pre-pupae', the BSF larvae crawl out of the substrate themselves. This is sometimes referred to as 'self-harvesting', as it eases the separation of BSF larvae from the substrate, which can help to lower costs (Wong et al., 2019). The nutritional composition also changes throughout the entire lifecycle, including the level of chitin, a polysaccharide that may impair the digestibility of other nutrients, which is much higher at the pre-pupae stage (Magalhães et al., 2017; Wang et al., 2020; Liu et al., 2017). The black-box approach of the model in this study does not account for these differences between the testing procedures of the studies in the literature research.

4.3. *Main findings and recommendations for future research*

A mix of draff and pot ale syrup has been identified as the most promising rearing substrate in Scotland, based on the current availability and utilisation of these biomass streams, as well as the reported performance of BSF larvae on similar substrates. Lab tests are required to examine the actual suitability of whisky by-products as a substrate. Such tests should not only focus on draff mixed with pot ale syrup in the mentioned 3:1 ratio, which was chosen to resemble the raw material makeup of DDGS. Instead, a range of ratios can be experimented with, and different evaporation densities for pot ale syrup can be tested. Using higher inclusion rates of pot ale syrup at the expense of draff could lower the environmental impact of BSF larvae from whisky by-products, since pot ale is still largely underutilised. Moreover, less-concentrated pot ale syrup with a higher moisture content may yield better rearing results whilst requiring less energy expenses for evaporation. Even when partially dewatered pot ale is unsuitable as a substrate on its own, it could be mixed with a relatively dry material to arrive at an optimal substrate.

The current move to bioenergy as a valorisation route for whisky by-products may impact the volumes of draff and pot ale available for insect rearing. Whether insect rearing can be considered as a more desirable valorisation route than bioenergy generation, depends on the associated environmental benefits, economics, and government objectives. The Sustainable Development Goals (SDGs) of the United Nations' Agenda 2030 could offer some guidance on determining the optimal valorisation routes for whisky by-products. However, trade-offs between of the different SDGs should be expected (Kroll et al., 2019). For example, bioenergy generation could ensure progress on SDG 7, affordable and clean energy, whilst insect rearing would reduce food waste, as targeted by SDG 12, responsible consumption and production. When following the EU food waste hierarchy, upcycling organic waste back into the food chain should be prioritised above energy recovery. Earlier research also indicated that the use of whisky by-products to replace soy in animal diets may realise a bigger reduction in greenhouse gas emissions compared to anaerobic digestion (Leinonen et al., 2018). Whether this also holds when these by-products are used to produce insect-based feed ingredients, requires further research.

With regard to economics, the present study provides new insights on the substrate costs and revenues that can be expected when producing insect-based feed ingredients from various biomass streams, including whisky by-products. Kang et al. (2020) can be consulted for estimations on the profitability of anaerobic digestion as a valorisation route for whisky by-products. Another scenario that could be investigated, is the rearing of BSF larvae on the residues, or 'digestate', left after the anaerobic digestion of whisky by-products or other biomass streams. Digestate from different types of treated materials has already been tested as a substrate for BSF larvae, with varying results (Lalander et al., 2019; Wee and Su, 2019; Veldkamp et al., 2021).

Under the current legislation, however, rearing insects for the production of feed ingredients is only allowed on substrates that are authorised as animal feed. This creates a situation in which insect rearing and animal farming compete over the same resources, affecting both the environmental and economic sustainability of insect-based feed ingredients. Therefore, regulations should be reviewed to allow insect producers to utilise "true waste" products, which can result in higher environmental benefits at lower substrate costs. In the meantime, pot ale presents a unique opportunity, as a material that is both legal as well as underutilised, and that possesses favourable characteristics when concentrated into a syrup and/or mixed with other materials. By supporting research, stakeholders involved in whisky distilling, insect rearing, and salmon aquaculture could further investigate this opportunity.

5. Conclusions

This study assessed the feasibility of Scottish biomass streams as substrates for the production of insect-based salmon feed ingredients. Substrates containing spent grains and/or spent yeast from beer brewing resulted in some of the highest substrate cost margins, were among the most productive, and yielded LMs with relatively high CP contents. Moreover, these materials are produced year-round, homogeneous in their composition, geographically concentrated, and legal for the use in insect rearing. However, only limited volumes are available and the majority is already valorised as animal feed. As such, brewery by-products cannot be classed as 'underutilised', compromising the environmental benefits any resulting LM could offer compared to fishmeal and soybean meal.

On the contrary, distillery by-products can be classed as underutilised, as draff is increasingly burned for bioenergy and the majority of pot ale remains unused. The physical properties and nutrient compositions of draff and pot ale syrup are comparable to spent grains and spent yeast respectively. Therefore, it is argued that the performance of BSF larvae on a mixture of these distillery by-products is likely to be comparable to the performance observed on beer by-products. Calculations show that, if this proves to be the case, 8.5 thousand tonnes of LM and 3.8 thousand tonnes of LO may be produced at the largest geographical hotspot of distillery by-products in Scotland. If the obtained LM and LO would then sell for the same prices as fishmeal and rapeseed oil, BSF larvae rearing would add almost 100% more value to the utilised draff and pot ale syrup. Moreover, this would upcycle the otherwise burned nutrients from draff back into the food chain, and provide an additional valorisation route for pot ale.

Based on these results, BSF larvae reared on whisky by-products have the potential to feed Scottish farmed salmon in the future. More studies are required to examine and optimise the actual suitability and feasibility of whisky by-products as a substrate for BSF larvae rearing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: This manuscript is based on the dissertation that Georges-Jan J.E. Wehry submitted in August 2020 for completion of the MSc Sustainable Aquaculture at the University of Stirling. His MSc tuition fee was covered by a scholarship from the Sustainable Aquaculture Innovation Centre, based in Scotland. From September 2020 to December 2021, Wehry was employed by ForFarmers N.V., an internationally operating company manufacturing and distributing feed for terrestrial farm animals.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clet.2022.100520.

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