EUROGROUP FOR ANIMALS

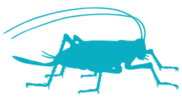
Insect farming and sustainable food systems: the precautionary principle

Ten species of insects are authorised for food or feed in the EU, and the number is likely to grow over the coming years. Insects are seen as a solution to food sustainability both as a replacement feed for animals and as a protein source for humans.

However, the situation is not clear-cut. Industrial insect production does not go hand in hand with sustainable food systems. In fact, behind what European Commission experts call *'an overwhelming lack of knowledge'*[1] surrounding the industry, there are a number of issues that require policy makers and the sector to adhere to the precautionary principle.

This review by Dr Helen Lambert - animal welfare expert - focuses on the behavioural needs and welfare of the farmed insects. The welfare of insects reared in industrial facilities is often brushed aside when discussing the political and economic pertinence of insect farming. Yet as the findings in this review show, insect welfare is connected to other problematic areas for the insect industry, such as pathogens and diseases, energy consumption and the inefficiencies of feeding insects agricultural products that could be fed directly to animals, or indeed, people.

The European Union is committed to developing a fair, healthy and environmentally friendly food system, and acknowledges the need to move to more plant-based diets. Moreover, the Farm to Fork strategy recognises the importance of animal welfare and its interconnectedness with human health and the environment in line with the One Health principle.



TAKING INSECT WELFARE AS A STARTING POINT, THIS REVIEW HIGHLIGHTS THAT:

1. The EU needs to ensure that insect production does not exacerbate the food-feed competition.
2. Insects used in feed must not slow progress towards the European Union's sustainable food system objectives.
3. The welfare of insects needs to be taken into account as they have behavioural needs and cognitive abilities.
4. Genetic manipulation of insects is part of the business model, it must be approached with caution as it can give rise to new welfare concerns.

The EU needs to ensure that insect production does not exacerbate the food-feed competition

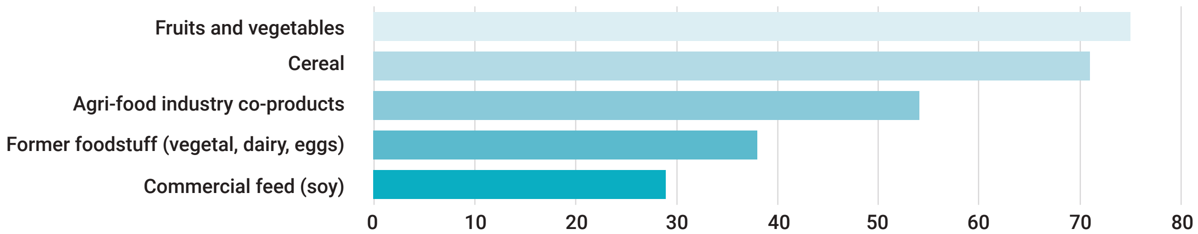
One of the main arguments in favour of insect farming is that insects can feed on waste and other products not fit for human or animal consumption and upcycle them into protein. Notwithstanding ingredients that are not authorised in insect substrates for hygiene and health reasons, not all insect species can thrive on waste or poor quality substrates.

Crickets, for instance, are often fed on vegetables, chick starter feed or other commercial feeds. This is necessary to ensure they grow to a harvestable size and to keep mortality rates low. Absence of adequate food could also trigger competitive behaviour between individuals and cannibalism, leading to injury and death.

In fact, according to the industry association IPIFF, producers use a number of different ingredients. About three-quarters use fruits, vegetables, and cereal. These are resources that could be used for direct human consumption or fed directly to extensively reared chickens and pigs. Around a third of insect producers use commercial feed which can include soy.

SUBSTRATES USED BY INSECT PRODUCERS

(PERCENTAGE -%- OF PRODUCERS USING EACH SUBSTRATE) Source: IPIFF vision paper on the future of the insect sector - Survey of IPIFF members - March 2018



Feeding insects ingredients that could be consumed directly by animals or people is inefficient. The European Union is mindful of the need to reduce the food-feed competition[2] and has set out objectives in its Farm to Fork strategy to make the food system more resilient. This resilience objective has, unfortunately, taken a new dimension with the tragic war in Ukraine that is putting pressure on the EU's feed supply chains; diverting crops for food to feed industrially farmed animals.

If the insect industry ramps up at its forecasted rate, there could be 45 trillion to 50 trillion[3] individuals produced by 2030. It is, therefore, fundamental that this new insect-producing industry does not increase the competition between producing food for people and for feed.

[1] European Commission - Platform on sustainable finance: technical working group, August 2021. https://ec.europa.eu/info/sites/default/files/business_economy_euro/banking_and_finance/documents/210803-sustainable-finance-platform-report-technical-screening-criteria-taxonomy-annex_en.pdf

[2] Towards a sustainable food system, group of scientific advisors to the European Commission, scientific opinion March 2020: https://op.europa.eu/en/publication-detail/-/publication/ca8ffeda-99bb-11ea-aac4-01aa75ed71a1/language-en

[3] Calculation based on "No longer crawling, insect protein to come of age in the 2020s" de Jong, Rabobank, 2021 and Shishkov O, Hu M, Johnson C, Hu DL. 2019 Black soldier fly larvae feed by forming a fountain around food. J. R. Soc. Interface and Lundy M., Parella M. 2015. Crickets are not a free lunch: Protein capture from scalable organic side-streams via high density populations of Acheta Domesticus. https://doi.org/10.1371/journal.pone.0118785

Insects used in feed must not slow progress towards the European Union's sustainable food system objectives

Promoting large-scale insect farming to feed pigs and poultry will sustain intensive animal production models instead of facilitating the transition to a sustainable food system as envisaged by the European Union's Green Deal and its Farm to Fork Strategy.

The sustainable food system promoted by the EU should focus on reducing the amount of animal products and supplying them from systems with higher welfare standards. Boosting insect farming for animal feed will sustain factory farming with its serious animal welfare concerns. Indeed, the European Commission's Agricultural Outlook[4] forecasts that the increased supply of insect meal and lower prices could support conventional intensive animal production if the practice is fully commercialised and existing restrictions lifted.

This could also compromise other sustainability and human health goals of the strategy, such as reducing meat consumption by moving to more plant-based diets.

The welfare of insects needs to be taken into account as they have behavioural needs and cognitive abilities

This review raises the key question of whether farmed insects are sentient, capable of subjective experiences such as pain and fear.

There are over 2,000 identified edible insect species, consequently, determining sentience for each is a considerable task. However, evidence regarding insect sentience exists, both for individual species, and across the taxa.

Although the subject has not been fully researched, the scientific community suggests applying the precautionary principle when considering the capacity of insects to suffer. This means that insects should be treated humanely both as they are reared and at the time of slaughter. Throughout their lifespan, insects should be raised in ways that respect their species-specific needs and behaviours, despite industry productivity considerations.

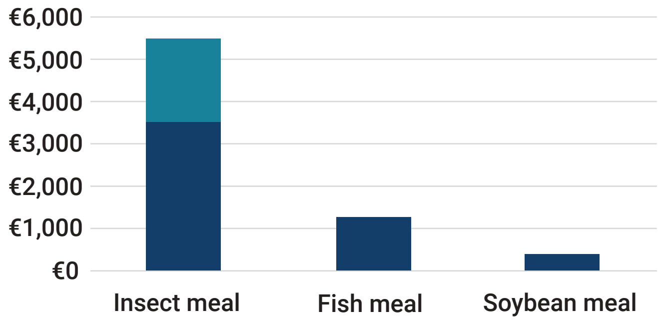
For the EU's food system to be sustainable, insects should absolutely not be reared intensively as feed for factory farmed animals.

Genetic manipulation of insects is part of the business model, it must be approached with caution as it can give rise to new welfare concerns

As a mass production feed industry, insect farming is still costly. Insect meal is 3 to 4 times more expensive than fishmeal and ten times more expensive than soy meal.

A path to cost reduction is to increase the number of individuals produced in facilities. However, the common understanding that insects are gregarious animals and that the resulting cannibalism is normal, is an oversimplification.

COST OF INSECT, FISH AND SOY MEAL PER TONNE, OCTOBER 2021



Source: Rabobank 2020 and Indexmundi 2021

Certain species thrive in isolation as well as in gregarious settings. Even with gregarious species, overcrowding not only hinders their capacity to behave normally, but can be a trigger for abnormal aggressivity and cannibalism. Density in facilities, therefore, matters.

Moreover, to be competitive, the insect production industry is also turning to genetic breeding and genetic selection. In fact the industry is candid that its competitiveness is dependent on insects growing bigger and faster.[6] For this reason, industry leaders Ÿnsect, Protix, Beta Bugs and others are all investing in insect genetics.

This report argues that genetic manipulation can give rise to new welfare issues in insects as has been the case in the genetic manipulation of vertebrates.

Conclusion: the precautionary principle should be applied before further species authorisations are given to ensure industrial insect farming is compatible with the EU's objectives

Insect farming is not necessarily compatible with a more sustainable food system. It raises new animal welfare issues as well as supports, rather than limits, intensive animal farming and its consequences on environmentally unsustainable and unhealthy high-animal product diets.

The precautionary principle needs to be applied in legislating the insect production sector. It is imperative to ensure that its development is compatible with the EU's objectives for a sustainable food system.

Further EU regulatory authorisations for industrial production of insect species should not be given until:

- There is solid scientific evidence on their welfare needs, including regarding the method of slaughter.
- The development of the insect production sector fits in with the EU's move towards a sustainable food system rather than hindering it.

[4] European Commission, 2020, EU agricultural outlook for markets, income and environment, 2020-2030, Directorate General for agricultural and rural development, https://ec.europa.eu/info/sites/default/files/food-farming-fisheries/farming/documents/agricultural-outlook-2020-report_en.pdf

[6] Wired, February 2022. https://www.wired.co.uk/article/insect-pet-animal-food

INSECTS FOR FOOD AND FEED IN THE EU

DR HELEN LAMBERT, MARCH 2022

EXECUTIVE SUMMARY

There are currently 10 insect species approved for feed for livestock and food for human consumption in the EU. However, the list is likely to grow as there is a global pressure to view insects as the solution to food security, both as a replacement feed for livestock, and directly as a protein source for humans.

Many view farming insects as a more ethical alternative to farming vertebrates, but this is based on a presumption that they are not sentient, and capable of pain and suffering. Scientists do not yet have conclusive evidence for insect sentience, but this does not mean that they are not sentient. It is just a reflection of the limited attention this sector has received as yet. Many suggest that, when considering insect welfare, we should adopt the precautionary principle, and treat them as if they are sentient, and consider their wellbeing in farming practices. With this in mind, this report explores what is known about each of the farmed insect species in terms of their natural behaviours, and how these may be affected by farming practices.

Production facilities: density matters

Some of the key welfare concerns that are covered in this report include the densities at which each species is kept at. There are no consistent criteria or guidance for the densities at which farmed insects should be kept, and often scientific research draws different conclusions.

This is primarily because results regarding optimum densities cannot simply be scaled up, as other factors such as environmental temperature, humidity, flying space, and surface area can all vary depending on the type of structure. Too high densities can cause increased mortalities, injuries, cannibalism, poor reproductive performance, and poor growth in most of the farmed insect species.

This is, therefore, an important area for future research, as not only are species-specific criteria needed for each species, but these also need to consider the impact of different systems and scales.

Substrates: the right feed is necessary

Feed is another important area of focus, as the right food can not only improve production but also potentially insect welfare. The desire to use waste streams for a circular economy may not always be in the best interests of the insects, though, and can cause increased mortalities. Furthermore, insects show preferences for certain types of feed, and so understanding these preferences can be critical for ensuring wellbeing and promoting good development.

Slaughter: no consensus on humane practices

Handling and slaughter is also an area where welfare can be compromised. If we are to consider insects as sentient, then they should be given a humane death. Unfortunately, there is no consensus on what a humane death looks like for any of the farmed insect species. Current guidance is based on assumptions, rather than any empirical investigation into behaviour and physiological responses to slaughter methods

Species-specific regulations: one size does not fit all

As this report shows, the behaviour and needs of farmed insects differ considerably. This means that insect welfare regulations need to be both species-specific and context-specific. Merely suggesting that insects should be kept as naturally as possible is both unhelpful and unrealistic, and places the emphasis on the farmer to perform due diligence and research what exactly is natural for their insect species.

Given that insect farming has procedures which are far removed from natural conditions, such as slaughtering larvae, such a suggestion is also impossible. Instead, species-specific regulations that are based on the behavioural and physiological needs of the insects are needed.

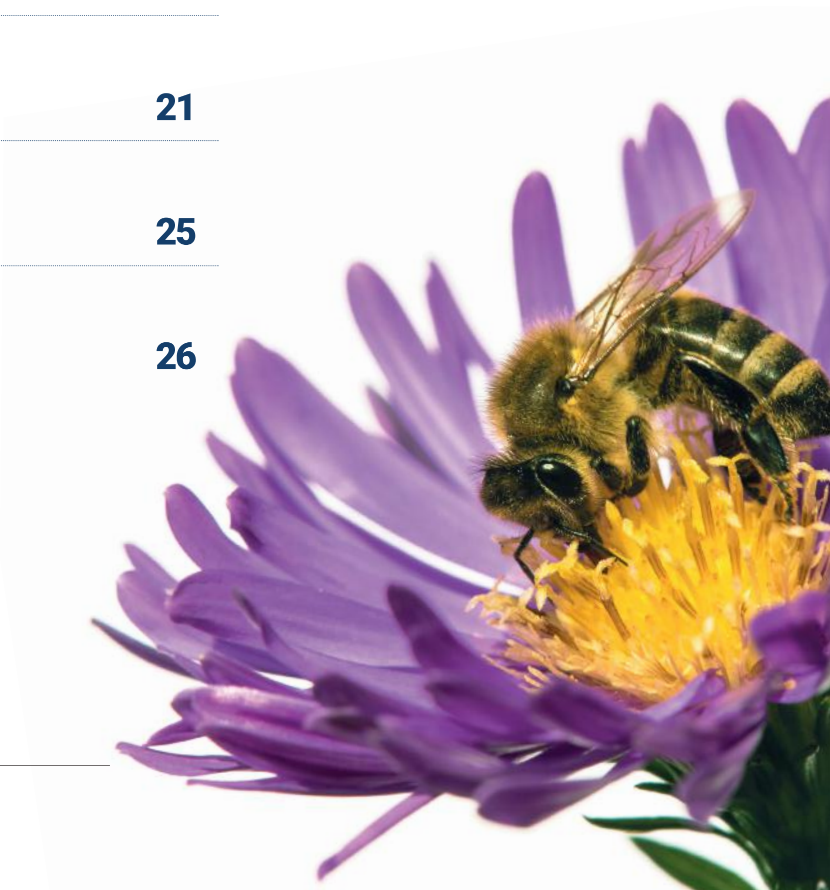
To account for the many styles of systems currently being used, the regulations should focus on animal-based indicators, to assess welfare from the individual's perspective (mortality rates, reproduction rates, performance of natural behaviours).

The precautionary principle is recommended

This report ends with the following recommendations;

1. The precautionary principle should be adopted and farmed insects must therefore be viewed as sentient, and treated as humanely as possible;
2. Species-specific regulations are needed for each of the farmed insect species, utilising meta-analyses to inform best practice, and scientific research should be conducted to fill the gaps;
3. Welfare outputs, or animal-based measures, should be used alongside resource input measures, to ensure welfare is considered from the individual's perspective; and
4. Where insect farming practices significantly impede natural behaviour, such as flight in the migratory locust, and feeding in the adult black soldier fly, research should be conducted to determine the impact of inhibiting natural behaviours, and where necessary the suitability of these species to farming.

CONTENTS



1. INTRODUCTION

Policy setting

In September 2021, Commission Regulation (EU) 2021/1372 was updated to allow the EU Member States to use insect protein for pig and poultry feed, as well as for pet food. This builds on the 2017 authorisation of insect protein for aquafeed (Commission Regulation (EU) 2017/893). The European Commission updated it again in November 2021 to allow the use of silkworm processed animal proteins for feed.

This brought the list of authorised insect species up to eight, including the black soldier fly, the housefly, the silkworm, and different species of mealworm and crickets (European Commission, 2022).

In terms of human consumption, there are three species approved as food and available for sale in the EU market. These are yellow mealworms, migratory locusts, and more recently the house cricket (European Commission, 2022). It is likely that the lesser mealworm, the banded cricket and the Western honeybee (broodstock[7]) will also be included in the future

Entomophagy

The practice of eating insects, known as entomophagy, is not a recent phenomenon, as it was once a core part of our ancestors' diets, and insects are still a dietary staple for many cultures around the world (Akhtar and Isman, 2018; Ramos-Elorduy, 2009). In the last decade, as environmental concerns have increased, the use of insects as a source of protein has become a potentially environmentally friendly alternative to traditional livestock (van Huis et al., 2013). The receptive market for eating insects in Europe is still relatively niche, however, and overcoming cultural disgust is a significant hurdle (Sogari et al., 2019). To overcome this issue, most of the products being developed utilise powdered insects (Halloran et al., 2014; Reverberi, 2020; Yen, 2009).

The Food and Agriculture Organisation of the United Nations (FAO) suggests that there are multiple benefits of eating insects, stating that they are safe and nutritious and that farming insects offers wider societal and economic benefits (van Huis et al., 2013). Insects are also more efficient compared with traditional livestock, as not only do they need less space, feed and water, but they can also convert their food to protein much more efficiently than cows, pigs and poultry (Dicke, 2018). Some insects can also be reared on agricultural waste streams, creating a desirable circular economy (Dörper et al., 2020).

Insects as feed

In terms of financial investments, most attention is on using insects as feed for livestock. This area does not have the same cultural barriers to acceptance and potentially offers considerable benefits in terms of cost, efficiency and sustainability, compared with growing soy and fishmeal (Halloran et al., 2014).

Many of the proposed benefits for using insects as feed are the same as those for human food, including the potential for circular economies; where insects are reared on slurry, or food waste, as well as reducing emissions and requiring fewer resources (Dicke, 2018; Dörper et al., 2020). However, as yet, these proposed benefits are still under scrutiny, and farming insects for feed may not be as beneficial to the environment as is postulated.

For example, the European Commission predicts that large-scale rearing of insects as feed will boost animal agriculture and aquaculture, leading to increased emissions from these sectors (European Commission, 2020). The desired circular economy from insects being reared on waste streams may not always be logistically possible (Lundy and Parrella, 2015). There are also valid concerns that using insects as feed will only exacerbate the welfare issues associated with current livestock farming, and perpetuate intensive animal agriculture (European Commission, 2020). The push to farm insects for food and feed is also at odds with the EU's Farm to Fork Strategy[8] which advocates for citizens to move to a more plant-based diet, and for research to focus on developing meat alternatives and plant proteins[9].

[7] Broodstock is the collective term for the eggs, larvae and pupae produced by honeybees. In terms of human consumption, it is the larvae (small white grub like stage) and the pupae (metamorphosis stage) which are eaten.

[8] https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1590404602495&uri=CELEX:52020DC0381

[9] https://www.eurogroupforanimals.org/news/analysis-eu-campaigns-promote-meat-eggs-and-dairy

2. DISCUSSION OF INSECT SENTIENCE AND WELFARE

A key question regarding insect farming is whether these farmed insects are sentient, capable of subjective experiences such as pain and fear (van Huis, 2020a). Establishing sentience is challenging, even for some vertebrates, and the sheer number of insect species makes for a daunting task, as there are at least 2,111 edible species (Jongema, 2017). However, there are pockets of evidence regarding insect sentience, both for individual species, and across the taxa (Lambert et al., 2021).

For example, although insect brains differ widely from vertebrate brains, there is an overall similarity between the functional structure of key parts of the vertebrate brain (midbrain, and the insect brain (Barron and Klein, 2016. Both vertebrate and insect brains have specialised regions that process information, such as the position of the moving animal in space, their state (hungry, thirsty, too hot, too cold, etc, information from their environment, and the relevance of different stimuli with regard to the environment and themselves.

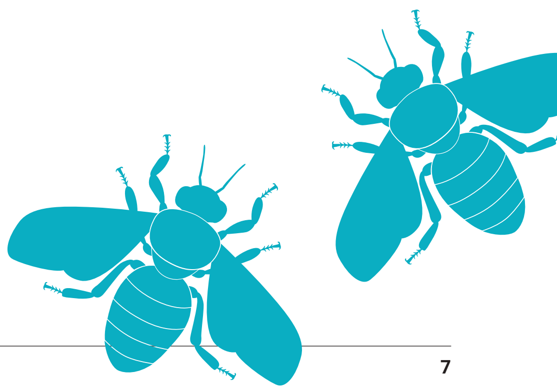
> "Although insect brains differ widely from vertebrate brains, there is an overall similarity between the functional structure of key parts of the vertebrate brain, and the insect brain."

The unified processing o f t his i nformation s een i n both vertebrates and insects, not only allows for effective decision making, but is thought to be a key feature of subjective experience, and therefore sentience (Klein and Barron, 2016. Neuroscientists Klein and Barron suggest that the similarities between the insect brain and the midbrain of vertebrates may, therefore, be evidence for insect sentience. They are cautious in their conclusions, however, and suggest that there may still be other neural features required for sentience in the vertebrate brain, which insects do not have (Klein and Barron, 2016). Although their conclusions are still being debated in the scientific community (Adamo, 2016; Cruse and Schilling, 2016, they do offer food for thought.

Requiring absolute proof of sentience in insects is likely to take some time, and may cause some species to be unfairly disregarded as incapable of suffering (Birch, 2017; Proctor et al., 2013). In the meantime, we can draw upon our understanding of insect behaviour, to determine to what degree industry farming practices may contradict their welfare needs.

And although we may know little about their sentience, there are arguments from the scientific community that the precautionary principle should be adopted when considering the capacity of insects to suffer (Baracchi and Baciadonna, 2020; Birch, 2017; Klein and Barron, 2016; Lambert et al., 2021; van Huis, 2020b). This means that insects should be given the benefit of the doubt when farmed for food and feed, be treated humanely, and raised in conditions as closely resembling natural conditions as possible (Boppré and Vane-Wright, 2019; van Huis, 2020a).

Unfortunately, this may not be conducive to optimal production, as industry may place insects into conditions that are not species-appropriate to maximise production or to maintain nutritional quality (van Huis, 2020a). To what degree this affects their wellbeing is unknown. Many of the practices involved to breed, rear and slaughter insects for food and feed are not transparent, and processes are often guided by best judgement or logistics, rather than by an assessment of the welfare implications (Bear, 2020, 2019). As a result, research into the impacts of farming on the wellbeing of insects is greatly needed.



3. CAVEATS

Unlike vertebrates, insects have a unique trait in terms of their life cycles, in that their infant and adolescent physiological form differs significantly from the adult form. As a result, the behaviour and potentially the welfare needs of the adult insect will differ greatly from those of larvae. This has been addressed in this paper by discussing the adult and larval forms where necessary. The same may also apply to their sentience, as the brain undergoes significant changes throughout metamorphosis, and so evidence for sentience may need to be determined for each stage of the life-cycle.

Many of the behavioural studies performed on insects have been performed as part of the industrialisation of the species for farming. The context in which the animal has been studied, however, has significant implications for how translatable the research is to industry (Miranda et al., 2020). If, for example, the species was studied on a small-scale, their behaviour and physiological indicators of welfare (growth, mortality rates, etc) may differ vastly from when they are kept at a larger, industrial scale. Insect farming operations range from small-scale operations to mass-industrialised set-ups, with various rearing structure designs. Consequently, the number of individual insects in each container may vary from anywhere from a few hundred larvae to >10,000 (Miranda et al., 2020). Although the literature presented here is used to provide an understanding of the insect species' behaviour, it is important to note that how the species behaves in the wild may differ from how they behave on a farm.

Another key consideration is the likelihood of using new technologies to genetically edit insects for production. To make production more efficient and cost-effective, industry is already exploring ways to genetically modify insects to make them bigger, faster and more efficient (Carere and Mather, 2019; RDA, 2018; van Huis, 2020b). Not only does this raise wider issues, such as the impacts on ecosystems, and the welfare of the involved during the experimental process, but it also means that potentially, any understanding of the sentience or wellbeing of the insects being farmed, may be subject to change if they are significantly modified genetically. For example, editing a cricket to grow quicker, may also introduce welfare issues, as that cricket may then be more susceptible to disease, or more likely to suffer in higher densities. The consequences of such editing would need to be fully explored, both from a production perspective, but also from the insect's perspective.

4. OVERARCHING WELFARE CONCERNS FOR INSECT FARMING

In addition to those covered in each of the sections above, there are some overarching themes in terms of welfare that are relevant. For instance, what may be optimal in terms of production, such as lighting, densities, temperature and humidity, may not be best for the insect. Like with vertebrate farming, the emphasis is likely to be on finding a balance between mortality rates and costs (Niyonsaba et al., 2021).

Although some insects may tolerate total darkness, which producers may do to reduce costs (Erens et al., 2012), whether this is good for the insects' welfare is unclear.

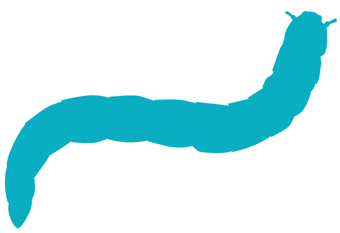
Premature mortalities are also an issue across industry. These may result in poor environmental conditions, which result in issues such as cannibalism, over-heating, or disease (Erens et al., 2012). Diseases and pests can be a significant issue for farmed animals, and may be fatal or non-fatal. For example, fruit flies and mites are common pests around crickets, but the impact of these is unclear (Rowe, 2020). Poor nutrition or food contamination are also significant causes of premature mortalities, as are water-related deaths, as many insects are reared in high humidity environments and may drown in pools of water, or consume contaminated water (Rowe, 2020).

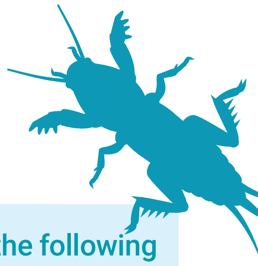
Injuries, whether fatal or non-fatal, may also be a cause of poor welfare, as with high densities injuries are likely to increase (Erens et al., 2012). For flying animals, damaged wings may be a significant issue, and damaged legs for all insects could lead to poor welfare, and an inability to fulfil natural behaviours.

Before slaughter, insects are often starved for a couple of days to empty their guts of the manure they have fed on (van Huis, 2020c). Although, this is not thought to be necessary from a food safety perspective (Bear, 2019; Wynants et al., 2017. The process of starvation may also be arbitrary if it is performed for too long, as many insects will resort to cannibalism when starved (Erens et al., 2012

Transportation is also a welfare consideration for insects transported live for reptile and poultry feed. Varying temperatures and densities are likely to be key factors in the survivability of these insects and their welfare. Particularly as research efforts have been focussed on understanding how to increase profits by transporting as many insects as possible in one container (Shishkov et al., 2019b). As a result, high rates of mortality during transportation are commonplace (Rowe, 2020.

Hygiene is a considerable challenge for many insect farms, and the implications for poorly managed systems can be significant, in terms of welfare issues and mortalities from diseases. There are, of course, safety considerations in regards to hygiene for insects used for food and feed, and the EU is drafting regulation regarding this subject (European Commission, 2019. There is however, a clear need for requirements regarding hygiene practices, and appropriate levels for each of the farmed species.





5. CONCLUSION AND RECOMMENDATIONS

The behaviours and needs of farmed insects differ considerably. This means that insect welfare regulations need to be both species-specific and context-specific (Delvendahl et al., 2022. For example, there are likely to be significant differences in considerations for small-scale farming compared with large-scale farms, and many of the criteria regarding densities and environmental conditions cannot simply be scaled up.

Furthermore, a blanket recommendation to *'provide as natural conditions as possible'* which is commonly seen in this context (Carere and Mather, 2019; IPIFF, 2019), is both unhelpful and often unachievable in industry. Not only would this place the task of researching and establishing what is *'natural'*, upon the farmers, but it is also at odds with fundamental processes within the industry, such as the routine slaughter of larvae.

Considering that there is a large range of living conditions and feed requirements for the different insect species, and there are still uncertainties over what is optimum, sweeping recommendations such as these, not only make it challenging for any farmer who wants to adhere to the regulations, but also provides significant leeway for breeches, which may not be in the interests of the insects.

Species-specific regulations are therefore required for each of the EU approved insect species, which account for the different contexts and environments that may apply. In addition, to account for the many styles of systems currently used, regulations should focus on welfare outputs[10] to assess welfare from the individual's perspective.

Although many see farming insects as a more ethical alternative to farming vertebrates, this is based on a presumption that they are not sentient and capable of pain and suffering (Gjerris et al., 2016. It is important to note that an absence of evidence for insect sentience is not evidence of absence. In comparison with other taxa, research into insect sentience has barely scratched the surface, and so it may be that as things progress, science can gain more understanding of the subjective minds of insects.

In the meantime, it is suggested here, and by many others (Baracchi and Baciadonna, 2020; Lambert et al., 2021; van Huis, 2020a), that in regards to insect sentience, the precautionary principle should apply. This means that until proven otherwise, farmed insects should be treated as if they are capable of feeling pain and other important subjective experiences, and be farmed and killed in ways that would be considered humane, based on their natural behaviour, and scientific understanding of their physiological needs.

This viewpoint is endorsed by key figures in the field such as Professor van Huis, who is the Chief Editor of the Journal of Insects as Food and Feed, and author of the 2013 FAO book *'Edible insects: future prospects for food and feed security'* as well as many other key publications. In one paper, van Huis concludes that *'In general, the precautionary principle should be used, whereby we assume that invertebrates can experience emotions…the insect industry should take the necessary precautions so that insects are well treated'* (van Huis, 2020a.

With this in mind, I shall conclude with the following recommendations:

- In regards to insect sentience, the precautionary principle should be adopted. This means that until proven otherwise, farmed insects should be considered sentient, and measures should be taken to ensure their welfare.
- Species-specific regulations are required for each of the farmed insect species. These must be based on scientific knowledge of the species' natural behaviour and physiological needs, and consider the impacts of different scales and farming contexts. To address any gaps or conflicts, extensive meta-analyses of the scientific literature are required, as well as some targeted research to fill gaps in knowledge.
    - For example, there are many conflicting opinions regarding densities in the literature, and so a thorough meta-analysis for each species is required. Where insufficient research is available for conclusive criteria, empirical research should be carried out.
    - Currently, methods of killing and slaughter are based on assumptions regarding best practice, and no welfare assessments have been conducted. Scientific investigation is needed to establish the impact of different slaughter methods on the welfare of the different farmed insect species.
    - Misconceptions regarding the needs of some insect species may result in them being raised in sub-optimal conditions. For example, the adult black soldier fly feeds on a variety of foods in the wild, but is often starved in farms as they are thought to be incapable of feeding, or able to tolerate starvation.
- The species-specific regulations must incorporate output indicators of welfare, to mitigate the effects of different farming systems, and to view insect welfare from the perspective of the insect. These can be used alongside resource indicators for a holistic approach.
- Where insect farming significantly impedes the natural behaviour of insects, such as the confinement of wide-ranging insects like the migratory locust, and the non-feeding of adult black soldier flies, research should be conducted to determine the impact of inhibiting these behaviours, and where necessary the suitability of these insects to farming.
- Species-specific requirements regarding hygiene practices, and acceptable levels of bacteria, both in terms of food and feed safety, but also in terms of the welfare of the farmed insects, are required.

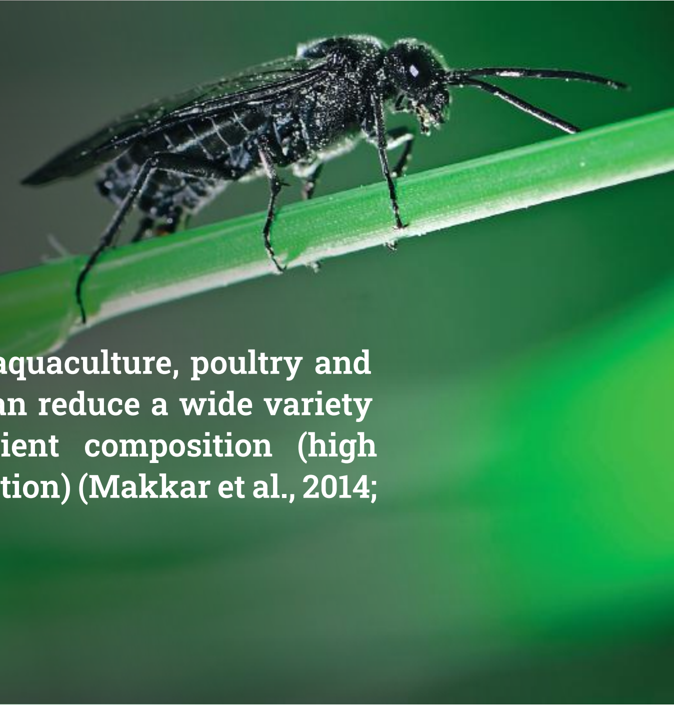
Given the impact that selective breeding for production has had upon farmed vertebrate welfare (broilers), limits regarding breeding, or genetically modifying insects to improve production should be set to ensure that modifications are made with the welfare of the insect in mind rather than only for the purpose of production at the expense of the insects' wellbeing.

[10] Input measures are the resources or factors that directly influence welfare, such as the type and amount of feed, the type of substrate, or the amount of space an animal is given. Output measures are the direct welfare outcomes of how the animals welfare is affected. Outputs are also referred to as animal based measures, as they consider the animal's perspective, and include measures like longevity, behaviour and health status.

BLACK SOLDIER FLY

(Hermentia Ilucens

The black soldier fly (BSF) is approved for feed for aquaculture, poultry and pigs in the EU. The black soldier fly larvae (BSFL) can reduce a wide variety of wastes, whilst offering feed with good nutrient composition (high protein, favourable amino acids and good fat composition) (Makkar et al., 2014; Rumpold and Schlüter, 2013).



WHAT TO LOOK OUT FOR:

- Density in rearing and transport
- Lighting, humidity and temperature at each development stage
- Shape of rearing bins
- Type of feed
- Feeding requirements of adults
- Flight space for mating

The total lifecycle of the black solider fly is around 45 days, and is comprised of four stages; egg, larva, pupa, and adult. The larval stage is around 18 days, the pupae stage is around 14 days, and the adult stage is around 9 days, depending on conditions. The female only lays eggs once, ovipositing[11] between 500-900 eggs, and then dies soon after (Makkar et al., 2014).

As larvae are used for feed, producers have to keep a separate breeding colony. They raise the adults in netted boxes and give them moist, rotting food for ovipositing. As mould is an issue, antibiotics are frequently used to treat the food (Yang, 2017). The farmers may also provide cardboard as an egg-laying substrate (Bullock et al., 2013). They typically remove the eggs and place them in a nursery bin for the larval phase (Rowe, 2020).

BLACK SOLDIER FLY LARVAE BEHAVIOUR

The behaviour of BSFL is of course markedly different from that of the adult BSF. This species is harvested at the larvae stage, and so the vast majority of the animals involved do not reach adulthood. Adult BSF behaviour is covered below, as large numbers of adults are still used for breeding purposes. The industry appears to prefer the term larvae, but some may refer to them as maggots.

Aggregating behaviour

BSFL tend to aggregate when in a confined area, piling up into corners (Shishkov and Hu, 2020). The larva at the bottom can withstand the weight of thousands of larvae on top of them and will rearrange themselves to mitigate the pressure (Shishkov et al., 2019b). When they aggregate into corners of their containers, they can generate significant force, which can split the container walls, or reach such heights that they can climb out of the bins, which can pose issues for farmers (Shishkov and Hu, 2020). The tendency of BSFL to aggregate is an important, natural behaviour, and even helps to facilitate early development (Bosch et al., 2020).

BSFL will aggregate around food, but individuals feed in bouts of around 5 minutes, taking frequent breaks, and only feed for around 45% of the time they are in proximity with food (Shishkov et al., 2019a). In an aggregation, this could cause 'road blocks' where resting larvae prevent others from feeding. To counteract this, the BSFL generate 'fountains' around food where the larvae feeding at the bottom of the pile get pushed upwards by incoming larvae, and then fall away from the food on top of the pile. This cycle continues, creating a fountain-like effect, allowing more larvae to access the food, circumventing the 'road blocks' and increasing the eating rate until the food is gone, at which point, the aggregation disperses (Shishkov et al., 2019a).

Food preferences

The diet of BSFL is an important economic consideration, as there is a fine balance between the cost of BSFL production, the cost of the feed substrate, its nutritional quality, its impact on larval development, the environmental footprint of their feed, and the safety of the ultimate food product (Bosch et al., 2020). BSFL are very good at being able to bio-convert[12] a range of organic waste or side streams into larval weight. Whereas studies have explored the rate at which BSFL larvae can convert such feed into larval mass, Parodi et al. (2020) explored whether the larvae had a preference for the type of feed they were given. Typically, BSFL are given only one type of feed in industrial conditions, and so it is not clear whether they would choose a different one if given the chance.

[11] Oviposition is the term used for egg-laying in insects.
[12] Bio-convert; the ability of the black soldier fly larvae to convert organic materials such as food waste into larval weight, which can be used as feed.

Naturally, BSFL grow on animal manure, whereas in industry they are given a mass-rearing diet of commercial products from various plant by-products. In their experiment, Parodi et al. presented BSFL with both the mass-rearing diet and pig manure simultaneously, each in diagonal corners of their container. In all of their trials, most of the larvae were found feeding on the pig manure, with only a few, or no larva at all, choosing the mass-rearing diet. Their findings demonstrate that BSFL show a strong preference for pig manure over the mass-rearing diet they are usually provided with in industry.

These findings were consistent across age, and independent of the type of feed they were reared on. Parodi et al. suggest that the larvae's preference may be due to the manure offering greater bacterial load, diversity and richness, and a higher pH compared with the mass-rearing diet. The larvae may have been responding to important olfactory cues related to reproduction when selecting the manure, as adult BSF naturally lay eggs in decomposing material like manure (Parodi et al., 2020.

Locomotory behaviour and self-harvesting

Younger BSFL and prepupae BSFL respond differently to different stressors such as light and moisture, and whilst larvae prefer dark moist areas, prepupae larvae seek lighter, drier areas to pupate in (Makkar et al., 2014. Some farms use this behaviour and house the larvae in specially designed containers, which allow the prepupae BSFL to crawl out, separating themselves from the younger larvae (Makkar et al., 2014. This 'self-harvesting' strategy efficiently separates the larvae and eliminates the need for hand-sorting (Giannetti et al., 2022.

Adult black soldier fly behaviour

Although it is the larvae of the BSF that is used for feed, the adult still plays a key role in reproduction. Most adult BSFs (69% mate within 2 days, and then oviposition usually occurs 2 days after mating (70% of the time (Abd El-Hack et al., 2020. Mating and oviposition occur throughout the year (Sheppard et al., 2002, but factors such as daytime, lighting, moisture, and temperature are influential (Tomberlin and Sheppard, 2002.

(Non)feeding behaviour in the adult BSF

Adult BSFs are often described as non-feeders, relying upon fat stores from the larval stage for the adult phase, as they are thought to not have functioning mouthparts (Abd El-Hack et al., 2020. In fact, the family of soldier flies (Stratiomyidae have fully developed muscoid (sponge-like type mouthparts and are described as nectar and pollen feeders (Bertinetti et al., 2019. In particular, BSFs may colonise beehives, exploiting them as an energy resource for both adults and larvae (Bertinetti et al., 2019. And, although adult BSFs may have difficulty absorbing solid particles, can use salivary secretions to aid absorption (Bertinetti et al., 2019.

Much of the guidance and research concerned with rearing BSFs is concerned with what to feed the larvae, whereas the adults are usually starved (Abd El-Hack et al., 2020; Makkar et al., 2014). Although the adult BSFs can utilise stored fat reserves, they can physically eat, and they will exploit resources in the wild (Bertinetti et al., 2019). Bertinetti et al. (2019) studied the effects of feeding adult BSF's four different diets; 1) no diet (control), 2) water, 3) a mix of sugar, bacteriological peptone and milk, or 4) agar with sugar. They found that feeding adult BSFs the agar or milk mix diets led to longer longevity of females by 1-2 days, compared with the control or water diets. There was no effect upon males. Providing a nutritious diet also increased the number of eggs the females laid three-fold, compared with the water or control diets, partly because the period of oviposition was 10 days longer for females fed the milk or agar diets. There were no effects on the hatchability of eggs (Bertinetti et al., 2019).

Macavei et al. (2020) had similar results when they fed adult BSFs no food, water, or sugar-water. In this study, both the males and the females lived longer when fed sugar-water, compared with those fed water or nothing. Sugar-water also resulted in the highest number of eggs being oviposited, and they also found lighting had a positive, although secondary, effect on the number of eggs oviposited (Macavei et al., 2020).

These findings have important implications for industry, as there are significant productivity gains from feeding adult females a nutritious diet (Bertinetti et al., 2019), or at the very least a diet of water along with lighting as a compromise in terms of production costs (Macavei et al., 2020). Naturally, adult BSFs feed on a variety of substances, and when in artificial environments, they live longer and are more productive when they feed, so there is also a potential welfare advantage to feeding adult BSFs.

Reproductive behaviour

Adult BSFs usually initiate mating on the wing, and wing fanning by both sexes is an important part of their sexual communication (Giunti et al., 2018). Males only approach females who are wing fanning, and the wing fanning of males during mounting attempts is also pivotal for female acceptance. There also appears to be a degree of mate choice by the monogamous females, as they appear to prefer approaching males who display shorter wing fanning behaviours (Giunti et al., 2018). BSFs prefer to mate in intense sunlight, and as the light intensity drops, so do the number of mating's (Tomberlin and Sheppard, 2002). Artificial light is not sufficient and results in few mating's, and infertile eggs (Tomberlin and Sheppard, 2002).

Oviposition

As well as preferring to mate in direct sunlight, female BSFs also prefer to oviposit in sunlight, as well as in sunny-shady areas (Park et al., 2016). The material available for ovipositing is an important factor, and BSFs will not oviposit unless the right substrate is available (Park et al., 2016). In particular, BSFs need sites with a small gap between them and sites where organic material is available (Park et al., 2016). The composition of the substrate is key, as when BSFs were presented with either food waste or calf feed in one study, they failed to sufficiently oviposit (Park et al., 2016). Oviposition was dependent on the ratio of calf feed in the medium, and 20% calf feed in a mixed medium was the most effective, as the flies laid significantly more egg clutches, compared with other ratios (Park et al., 2016).

WELFARE IMPLICATIONS FOR BSF AND THEIR LARVAE IN FARMING

Sentience and cognition

As the BSF is a relatively new species of interest, unsurprisingly the research performed to date has focused on how to rear them in the most efficient, cost-effective and safest way for their use in feed. BSFs also have no history in terms of experimentation, unlike other flies such as fruit flies. Therefore, as yet, there appears to have been no specific studies performed to assess whether BSFs are sentient, or capable of specific welfare relevant traits such as pain.

A lack of evidence does not mean a lack of sentience, however, some scientists suggest that all insect species are likely to be capable of important feelings such as pain (Klein and Barron, 2016).

Although the cognitive capacities of BSFs have not yet been explored, there are suggestions in the literature that BSFL possess some degree of cognitive capacity. For example, Shishkov et al. (2019b suggest that the memory span of BSFL may be instrumental in their ability to rearrange themselves whilst under compression in a pile of larvae.

Environmental needs

There has been considerable research performed in the past few years on BSFs regarding their use in industry. In terms of their welfare, the research into the causes and physics underlying the tendency of BSFL to aggregate is particularly relevant. In industry, BSFL are commonly raised in rectangular plastic bins, which can cause the larvae near the walls or corners of the container to become trapped, unable to crawl to their food (Shishkov et al., 2019a).

This has implications for industry and for the welfare of those larvae. Trapped larvae are likely to become starved, develop slower, gain less weight, and potentially die from starvation or overheating. Therefore, it is important that industry designs containers accordingly, or uses devices that gently rotate the larvae, so that all larvae have the chance to feed (Shishkov and Hu, 2020).

Managing environmental temperatures in an aggregating species can also be challenging, and if unmanaged, extreme temperatures can result in poor development and survivorship (Chia et al., 2018). Naturally, BSFL will cluster together and have natural strategies to cope with the compression and to ensure access to food sources. However, in artificial rearing, their natural tendency to aggregate and their sensitivity to subtle environmental changes in humidity and temperature can quickly result in sub-optimal and potentially fatal conditions (Erens et al., 2012; Makkar et al., 2014).

Research on adult BSFs has so far focused on oviposition sites, although this area is also relatively under-explored. Research does indicate that BSFs prefer some sites over others and that environmental factors such as lighting have significant effects on oviposition. Understanding under what conditions BSFs are most productive in terms of oviposition is likely to be beneficial for both industry and the needs of BSFs.

Adult BSFs are kept in netted cages, and so their ability to fly is restricted. It is not clear whether this impacts their welfare, but when we consider the confinement of vertebrates, keeping long-ranging vertebrates confined in small areas is a key concern, and so if we use the precautionary principle here, then there is potential for the size of the flying area to be a significant concern, and governance over the amount of flying space BSFs are given, is therefore required.

Densities

Farmed BSFL often need to be transported live so that they can be used as live feed or processed elsewhere. One study sought to explore how transportation costs could be reduced by packing the larvae more densely (Shishkov et al., 2019b). Unlike vertebrates, BSFL do not have any protective legislation governing their stocking density for rearing or for transportation (Shishkov et al., 2019b). This study showed that the larvae could withstand pressure equivalent to 53,000 times that from their weight, rearranging themselves to mitigate the force. Shishov et al. suggest that this means BSFL can be tightly packed in compressed containers without substrate, without causing them physical damage. However, research suggests that BSFL do not thrive in high densities (Jones et al., 2019), and so this is likely to negatively affect their behaviour.

> “Larvae who are thriving are beneficial to industry, as they have better weight gain, are quicker to develop, and therefore potentially more cost-effective.”

Density is also important for rearing larvae, and BSFL grow and develop quicker, reaching the prepupae stage 18 days faster at lower densities (500 individuals/4l), compared with at higher densities (2,000 individuals/4l) (Jones et al., 2019). Larvae are also larger (24%) at each life stage when kept in lower densities, compared with at higher densities (Jones et al., 2019). These positive effects may be due to the larvae being able to access resources more easily, or because the higher densities result in harmful, albeit subtle, changes in pH and moisture levels (Jones et al., 2019). Similar findings have been found in other studies exploring the impact of density on the life history traits of BSFL (Chia et al., 2018; Dzepe et al., 2019). It is clear, therefore, that although these larvae aggregate, this cannot be used as a justification for keeping them at high densities permanently, as aggregations are naturally temporary, and the larvae soon disperse once the food has gone.

For adult BSFs, this research again comes from the perspective of industry and boosting efficiency, rather than the welfare of the insects. Studies indicate that adult BSFs are most productive at high densities of 6,500 individuals/m³, compared with at lower densities (Hoc et al., 2019. Similar studies have found that there is a direct, positive relationship between adult densities and reproductive levels and that this can be enhanced by providing the right lighting ratio (Liu et al., 2022. However, high densities may negatively affect welfare by increasing the risk of injuries and competition for resources and oviposition sites (van Huis, 2020a. Flight space is particularly important for production, as mating is initiated on the wing (Abd El-Hack et al., 2020. Furthermore, large numbers of BSF in flight will lead to shading in artificially lit areas, which is detrimental to cues for both mating and oviposition (Tomberlin and Sheppard, 2002.

Consequently, individual reproductive success is likely to suffer from high densities, which may have welfare impacts on the individuals. Although industry can compensate for a loss of individual reproductivity by increasing densities, the efficiency of utilising each pair of flies in the breeding cage will decrease as density increases, and will eventually result in a reduced reproductive output overall (Liu et al., 2022). Therefore, not only are densities potentially important from a welfare perspective, but there are also production benefits for ensuring optimum densities from an individual perspective.

Feed

Studies have shown that BSFL show preferences for certain types of feed, such as manure, over commercially produced products (Parodi et al., 2020), and there are production benefits for providing preferred feed to BSFL (Miranda et al., 2020). These factors, such as improved survivorship, final body weight, and time taken to reach maximum body weight, are not only important for production but may also have implications for welfare, particularly in the case of early mortalities (Miranda et al., 2020; Parodi et al., 2020). Moreover, in vertebrates, providing animals with a choice is considered to be a way to provide control and a chance for good welfare. If we apply the precautionary principle to insects, then this would mean that giving BSFL access to their preferred feed could have positive welfare benefits.

Although adult BSFs can survive without food, using their fat reserves for reproduction and oviposition, this does not mean that starvation in industry is acceptable. Adult BSF perform better with the provision of some feed, and even just water can have positive effects upon production parameters. Therefore, it is likely that providing adult BSFs access to nutritious feed will also have welfare benefits, especially considering that they naturally feed on a range of substrates.

The common misconception that adult BSFs are incapable of feeding is, therefore, a harmful feature of the industry

Handling

Handling and slaughter are key areas of consideration in terms of welfare concerns in any farmed animal. Although it is not yet clear whether BSF are sentient, using the precautionary approach and giving them the benefit of the doubt means that it is important to consider how they are treated before and during slaughter. As discussed, BSFL have an inherent self-harvesting behaviour, where prepupae larvae crawl out of the container, and in specially designed systems they crawl into a waiting tray (Makkar et al., 2014). This reduces the need for manual sorting, which potentially has welfare benefits for these animals. Prepupae BSFL are known to freeze when they are handled, which is thought to be an anti-predator response (Giannetti et al., 2022). Therefore, there is a possibility that handling of prepupae BSFL may be stressful, and so designing systems that remove the need for handling them has benefits for both industry efficiency, and potential for reducing stress in the larvae.

Adult BSFs are not generally handled or slaughtered, as they are placed in the breeding cage at the pre-pupate stage and will stay there until they die.

Processing and slaughter

Following harvesting, the larvae are then usually weighed, washed, dried and then weighed again (Bosch et al., 2020). Processing methods following this step vary, but larvae may be frozen or killed in hot water and then frozen or dried. Bosch et al. suggest that the most humane method is to freeze them for at least 16 hours, then to blanche or shred them. Currently, research into killing methods focuses on the impact of methods on nutritional quality, texture or hygiene (Bessa et al., 2020; Melgar-Lalanne et al., 2019). Consequently, advice regarding the most humane method of killing larvae tends not to consider important behavioural responses or welfare impacts.

Can BSF be farmed humanely?

Since the BSF was recognised as an important species for industry, there has been a flurry of research into this species. So far, this has focused on their role as feed and improving their efficiency at converting waste into bio-matter. BSFL will survive and grow, providing the right environmental conditions are in place, such as humidity, moisture and temperature. To thrive, though, they need to be kept at lower densities and be given their preferred feed of manure. This, like with any aspect of livestock farming, brings issues of balancing cost and resources.

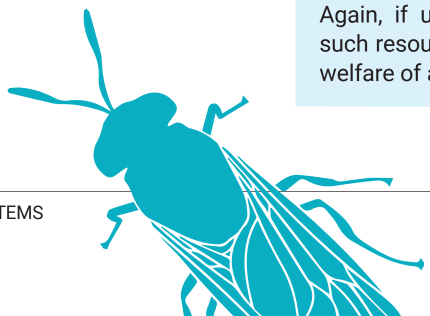
Whether it matters to the larvae if they thrive or merely survive, depends on their capacity for sentience. Larvae who are thriving are beneficial to industry, as they have better weight gain, are quicker to develop, and therefore potentially more cost-effective. Therefore, if the balance can be struck between cost and needs, then it seems possible that rearing BSFL can be done humanely with a few measures in place. The process of killing, however, needs attention, as methods currently vary, and there is no indication of what is the best option from the larvae's perspective.

In terms of adult BSFs, although they are relatively resilient to being farmed at high densities, and can even be done so without any feed or water, this is at odds with their natural conditions, and likely to be a welfare concern.

As mentioned in section above, focusing on densities at the individual reproductive level is one way to ensure individual welfare, as the ability to reproduce is likely to be an important element of a short-lived animal's wellbeing. It is important to note, however, that the studies performed on densities are not always performed at industry levels, and their findings are limited to the densities within a specific breeding cage size. Multiplying the cage size and densities used in these studies is not transferrable, as this would reduce the surface area for flies to land on, changing a core element.

Therefore, more research is needed on densities before thresholds can be established, and it may be that a focus on output indicators is required from a welfare perspective, so that such factors can be addressed from a case by case basis (the number of mortalities, individual reproductive success etc). In regards to other resources, although adults can survive and reproduce without feed or water, their productivity, and potentially their welfare, are improved by providing such resources.

Again, if using the precautionary principle, then providing such resources may have important positive benefits for the welfare of adult BSFs, as well as having production benefits.



COMMON HOUSEFLY

(Musca Domestica)

The common housefly (CHF) is approved for livestock feed in the EU. As with the black soldier fly, it is the larvae that are used for feed, and the adults for reproduction. The larvae are currently used in feed for fish, swine, poultry and pets, as well as for manure management (van Huis et al., 2020).

WHAT TO LOOK OUT FOR:

- Significant lack of scientific research
- Effects of temperature on lifespan and oviposition
- Impacts of crowding
- Flight space
- Sensitivity to light

The CHF is a worldwide pest and major carrier of diseases, as both the larvae and adults feed on manure and decaying organic waste. CHF larvae are a source of protein and lipids, and their nutritional value can also be enhanced by their diet (Makkar et al., 2014).

The lifespan of the common housefly is between 20-30 days for all four stages, depending upon the conditions (Francuski et al., 2020). The larval stage takes between four to 13 days at optimal temperatures, and adults can live between 15-25 days. The female CHF can lay eggs up to five times, laying around 130 eggs each time (Francuski et al., 2020).

Farms have specific facilities both for the larvae and the breeding colony. Poultry manure is commonly used for larvae, but other substrates, such as offal, pig manure, wheat bran, or rotten fruit may also be used (Makkar et al., 2014). Tanks or crates are filled with the substrate and then kept moist to attract the flies to oviposit. The eggs or larvae are then removed and placed into a rearing area, where they are kept at specific temperatures and humidity levels to aid growth before being harvested (Makkar et al., 2014).

COMMON HOUSEFLY LARVAE BEHAVIOUR

CHF larvae, also known as maggots, are less studied in terms of production compared with the BSFL. Given that both species are from the same order, Diptera, it is likely that some behaviours identified in BSFL also apply to the CHF larvae.

Migratory behaviour

CHF larvae migrate in their manure substrate to forage, and this can determine the extent of manure utilisation (Hussein et al., 2017). The larvae will migrate deeper as they age, reaching up to 3cm depth from the surface over a 7-day growth period (Hussein et al., 2017). It is not clear whether this is just a change in locomotive patterns, an effect of their growing size, or whether it is performed to access new areas of manure as the nutrients of the surface material become limited over time (Hussein et al., 2017).

Self-harvesting

The CHF larvae pupate within their rearing substrate, or along its edges (van Huis et al., 2020). It is possible to manipulate this behaviour though, and Čičková et al. (2012) found that placing a cover over the larvae's container, blocking out light and oxygen, resulted in the larvae migrating out of the container at the pre-pupate stage, and self-harvesting

Densities

CHF larvae are an aggregating species, but naturally, they have space to disperse. When in a contained environment, understanding to what degree crowding affects these animals is key. Hussein et al. (2017) compared the effects of rearing CHF larvae at two different densities (1 larva per gram of substrate and 7 larvae per gram of substrate) and found that the density did not significantly affect early migration rates, with only a 1.6% difference in the overall outmigration rate.[13] This meant that the increased competition did not result in the larvae leaving the manure too soon (Hussein et al., 2017).

Other behaviours

The CHF larvae are also an aggregating species, although far less research has been performed on this behaviour compared with the BSFL.

[13] Outmigration rate; the number of larvae moving out of the substrate, compared with those remaining.

COMMON HOUSEFLY ADULT BEHAVIOUR

Reproduction and oviposition

The scientific literature is still relatively sparse for adult CHFs, particularly compared with the BSF. Efficient egg production in this species is a current issue in industry, and there has been research into the most optimum conditions for adult CHFs to reproduce and oviposit. For example, Francuski et al. (2020) explored the effects of temperature on oviposition and found that adult longevity was shorter, and lifetime egg production was lower at 32°C than at 25°C. The higher temperature resulted in higher daily egg production in the first 7 days, reaching 50% of total egg production by day 6, but at the cost of reduced adult lifespan. Francuski et al. (2020) concluded that the higher temperature was therefore more cost-effective in terms of production, even though longevity was reduced, and therefore not necessarily optimal from a welfare perspective.

WELFARE IMPLICATIONS FOR THE COMMON HOUSEFLY AND THEIR LARVAE

Sentience and cognition

The CHF has not been a species of focus in terms of research into their sentience or cognitive capacities in recent years. However, there are a few examples of their cognitive capacities from older studies. In a series of experiments, CHFs were found to be capable of learning an escape response when exposed to aversive heat and light, and their behaviour was dependent on a contingency between their response and heat reduction. Although, whether this is evidence of learning, or just a phototactic response, is unclear. Nevertheless, CHFs are capable of some forms of learning and can be conditioned to extend or withhold their proboscis using a range of stimuli, from scents to light wavelengths (McGuire, 1984).

In another study, CHFs showed associative learning, as they could learn to associate the odour of a food source with the type of food, and then use the stored information about the food's odour when searching for it (Fukushi, 1983). The learned information was then retained for 3 hours with no decrease in performance, and was still present 18-22 hours later, although at a lower level. The researchers concluded that the CHF is capable of flexible learning, and not just performing stereotypic, automated patterns (Fukushi, 1983).

The memory of olfactory cues in CHF larvae has also been found to survive the metamorphosis process (Ray, 1999). In particular, the adult flies who came from larvae reared in aversively scented sawdust showed a preference for that same aversive scent when placed in a Y-shaped maze (Ray, 1999). Comparatively, the control flies, who had not been reared on scented sawdust as larvae, found both scents aversive.

Although there is, as yet, no research into their capacity for subjective experiences like pain and suffering, this does not mean that these animals are not sentient. They are known to have some cognitive capacities, and with greater attention, others may be found too, and so they are not the simplistic, automated beings they were once thought to be (Baracchi and Baciadonna, 2020).

Environmental needs

As so little has been done on the effects of different environments and pressures upon the CHF in industry, many questions remain unanswered. For example, what temperature is optimum for the CHF to facilitate reproduction, yet maintain longevity?

Research so far appears to present a trade-off, with the flies either reproducing faster and living shorter periods or living longer, reproducing more slowly, yet with overall greater numbers of eggs. To what degree the desires of industry compete with the impacts upon the flies is still to be explored.

For example, Francuski et al. (2020) suggested from their research into optimum temperatures, that it is most efficient to keep CHF adults at a higher temperature as they quickly produce eggs in these conditions, however, this conclusion fails to consider the potential welfare implications, as the flies also die more quickly in these conditions. This is evidence of what entomologist Professor van Huis suggests, in that keeping insects as naturally as possible is not always conducive to high production levels and represents one of the many conflicts that industry has with the needs of the insects they are farming (van Huis, 2020a). Adult common houseflies are kept in netted cages, and so their ability to fly is restricted. It is not clear whether this impacts their welfare, but when we consider the confinement of vertebrates, keeping long-ranging vertebrates confined in small areas is a key concern, and so if we use the precautionary principle here, then there is potential for the size of the flying area to be a concern.

Regarding CHF larvae, although they appear to be resilient in crowded conditions and do not migrate too early, it is not yet known whether crowding has any other undesirable effects. Other questions, such as their preferred rearing substrate, what impact air and substrate quality have, and the effects of handling and killing methods on the wellbeing of CHFs, are still unexplored.

Handling and slaughter

As with the BSF, little is known about whether or not the common processes used for killing and slaughter are humane or not. Handling is usually avoided by using alternatives such as the flotation method, where the manure is mixed with water, which causes the larvae and pupae to float and be collected by a sieve. Alternatively, the screening method is where the manure is spread in a thin layer on a screen net placed over a container. The larvae try to avoid the sunlight and crawl through the net into the container below (Makkar et al., 2014). The collected larvae are then washed, and killed in tepid or hot water, before being dried or milled (Makkar et al., 2014). Minimising handling for any larvae is likely to be favourable, both from a welfare and a production perspective, although it is not clear whether the larvae find any of these procedures stressful or not (Berggreen et al., 2018).

Can CHF be farmed humanely?

With so little known about this species in terms of how it responds to industrial rearing practices, it is too early to say whether this species can be humanely reared or not, and what protocols would be needed to protect their welfare. Further research into optimum conditions for this insect is needed.

YELLOW AND LESSER MEALWORMS

(Tenebrio Molitor & Alphitobius Diaperinus) and the adult darkling beetles

As with the larvae from black soldier flies and the common houseflies, mealworms also offer multiple benefits for industry as they can convert organic waste, and their larval form is rich in protein and fat, has a balanced amino-acids profile, and a good composition of minerals and vitamins for food and feed, (Adámková et al., 2017; Moruzzo et al., 2021).

WHAT TO LOOK OUT FOR:

- Balance of proteins and carbohydrates in feed mix
- Effects of lighting, temperature and humidity
- Mating opportunities for females and capacity to express sexual attractiveness for males
- Population density and overcrowding, providing suitable substrate for tunneling and pupation
- Stress induced cannibalism

In the EU, the yellow mealworm and the lesser mealworm are approved for feed for aquaculture, pigs and poultry. The yellow mealworm is approved for human consumption, and the lesser mealworm is likely to be approved soon. Both the lesser mealworm and the yellow mealworm are larvae from beetles from the darkling beetle family. As they come from the same taxonomic family, there are likely to be strong similarities in terms of behaviours and needs, and so they are grouped into one section.

It can take a yellow mealworm around 10-12 weeks to go from egg to adult size, and the adult beetles can live for another 8-12 weeks. Females may lay five to eight eggs a day, and about 300 in her lifetime (Andersen et al., 2017). The lesser mealworm can take between 6-14 weeks to develop into adults, and the adult beetle can then live for 3-12 months. The female adult lays on average 200-400 eggs in her lifetime, at a rate of 1-5 a day.

For production, farmers need to produce both the larvae and have a separate reproductive colony of beetles. The adult beetles are usually kept in large bins, and the eggs are removed and placed into separate bins for larvae rearing. Mealworm larvae are typically raised in large plastic bins that are insulated to maintain the heat generated from the mealworms (Rowe, 2020).

MEALWORM (LARVAE) BEHAVIOUR

Aggregating behaviour

Mealworms have an innate tendency to aggregate, and will prefer to aggregate in certain substances (lactic acid substrates) (Weaver et al., 1989). Mealworm aggregations are thought to occur when males emit aggregation pheromones, or in response to food odours (Hassemer et al., 2019).

Feeding preferences

The type of food that is offered to mealworms is an important consideration, as if they are not provided with optimal options, mealworms will show suppressed feeding behaviour, and will not enter the pupation stage (Rho and Lee, 2022). In one study, when yellow mealworms were offered one protein and one carbohydrate food, they ate both in equal measure for the first 15 days, and then showed a preference for the carbohydrate-based food for the following 15 days (Rho and Lee, 2022). In another experiment, mealworms were given different ratios of protein and carbohydrate foods, and those that were only given carbohydrates failed to eat sufficient amounts, and none of them pupated (Rho and Lee, 2022). Regardless of the feed mixes the larvae were given, all the pupae had similar body nutrient composition (apart from the 100% carbohydrate diet), which suggests that the larvae can regulate their diet for optimal body nutrient growth.

This has important implications for rearing mealworms, as mealworms cannot synthesise adequate amounts of essential amino acids to fulfil their nutritional requirements, and so these nutrients must be supplied through the diet (Grau et al., 2017). The amount of protein and carbohydrate given to mealworms also affects their larval development time, survival and growth, and so ensuring the right balance is available to them is important both for industry and from a wellbeing perspective (Grau et al., 2017). In particular, van Broekhoven et al. (2015) found that diets of yeast-derived protein appear to reduce larval development time, increase weight gain, and, importantly, from a welfare perspective, reduce mortality. Although, the impact of diet upon adult fecundity is another important consideration that needs greater attention (van Broekhoven et al., 2015).

Climbing and tunnelling behaviour

Mealworm larvae can climb and tunnel and will do so to look for protected pupation sites (Geden and Axtell, 1987). The provision of suitable substrate for pupation is important, and when larvae are not provided with soil or similar, they show increased climbing behaviour. Climbing and tunnelling behaviour also increases when the density level is too high, irrespective of soil provision, as competition for pupation sites increases, and the larvae are motivated to leave the area, and will even stall pupation as a result (Geden and Axtell, 1987). Other factors, such as the quality and availability of resources, can also influence tunnelling and climbing behaviour (Geden and Axtell, 1987). Adult beetles will also climb, and some will tunnel, although this is generally initiated by the larvae and exploited by the adults (Geden and Axtell, 1987).

Instar behaviour

Instar is the term used for the developmental stage between moults in an insect. The first instar is the larvae after hatching from the egg, the second comes after the first moult, and so on until pupation. The number of mealworm instars depends on environmental conditions, particularly temperature, but can reach up to 20 (Morales-Ramos et al., 2010). Later instars are inactive as they prepare for pupation. When ready to pupate, the larva will tunnel and construct pupal cells, where they will undergo the pupal stage (Wilson and Miner, 1969).

Adult mealworm (beetle) behaviour

The adult of the yellow mealworm is commonly referred to as the mealworm beetle (Tenebrio molitor), and the adult of the lesser mealworm is referred to using its scientific name; Alphitobius diaperinus.

Personality affects anti-predator response

The mealworm beetle has stable personality traits, which appear not only across time but also in different contexts. Krams et al. (2014) showed that beetles would respond differently to a simulated predator attack, in terms of how long it took them to become immobile, and how long they spent immobile when they thought a predator was close by.

Tonic immobility, or freezing, is an anti-predator response intended to reduce the chance of detection or to make the predator think the beetle is already dead. The beetles' behavioural responses reliably and consistently indicated the personality traits 'shyness' and 'boldness' in the beetles (Krams et al., 2014). Bold beetles were slower to become immobile, and quicker to become active again, whereas shy beetles were quicker to freeze, and were immobile for longer.

Personality affects reproductive success

The personality of female adult mealworm beetles also affects their reproductive success. Proactive, high risk-taking females produce more offspring, compared with low risk-taking females (Monceau et al., 2017). Their personality profile was, however, independent of their lifespan, as there was no difference between the lifespan of proactive and reactive (slow living, low risk-takers) females.

Phototactic behaviour

Both the larvae and the adult mealworms are negatively phototropic, which means that they grow away from the light (Ribeiro et al., 2018). They are also negatively phototactic, which means they will move away from light sources, and position themselves below the surface of the substrate during daylight hours. The adults surface in the darkness.

Reproductive behaviour

Female mealworm beetles are sexually receptive throughout their adult lives (Drnevich et al., 2001). Ad libitum mating or mating every 2 days results in the greatest number of eggs being laid. However, females mate more often than needed, and the reasons for this behaviour are not fully understood (Drnevich et al., 2001), nor are the implications, if any, of restricted mating opportunities upon their wellbeing.

Adaptive behaviour in response to resource availability

When there are food shortages and low temperatures, the Alphitobius diaperinus beetle responds by reducing oxygen consumption and locomotor activity (Renault et al., 2003). This *'sit and wait'* strategy is adaptive and allows them to recover as soon as resource availability and temperatures change. The strategy forfeits reproduction for survival, but when food is available, and the temperature increases, the beetles respond with hyperactive behaviour, although this is temperature dependent (Renault et al., 2003).

When immune-compromised male mealworm beetles face food shortages, they adapt by investing more into their sexual attractiveness, at the expense of their immune response and survival (Krams et al., 2015). When there is plenty of food, though, they concentrate on survival and immunity, rather than focus on the quality of their sex odours.

WELFARE IMPLICATIONS FOR MEALWORM LARVAE AND THE ADULT BEETLES

Sentence and cognition

Unsurprisingly, there has been no research on whether these species are sentient and capable of pain and suffering. There has, however, been some research into various cognitive traits. Although these abilities do not show a capacity for suffering, they do highlight that these animals possess a degree of intelligence, and some similarities with vertebrate animals.

As mealworm beetles are polygynandrous[14], sperm competition is a significant factor. To deal with this, and to optimise their chances, males have evolved several strategies that require a degree of numeracy (Pahl et al., 2013). For instance, beetles need to be able to adjust their mating behaviour in accordance with the situation and therefore need to know how many females and males are in the group. Numerical discrimination is the ability to distinguish between sets with more or fewer items, and is recognised as the foundation for higher numerical abilities (Carazo et al., 2009).

In their study, Carazo et al. found that male mealworm beetles were capable of numerical discrimination. They exposed the beetles to substrates with odours from different numbers of females (1-4), in different numerosity ratios (1:4, 1:3, and 1:2). The male beetles could discriminate sources of odours when it was 1:4 or 1:3 females, but not for 2:4 or 1:2. Their findings indicate that the males can chemically discriminate between two odour sources based upon the number of females contributing to the odour (when over 1:2). This cognitive ability means that the male beetles can maximise their chances, and head towards the odour source comprising the most females (Carazo et al., 2009).

Another strategy male mealworm beetles have evolved is to count, or at least estimate the number of male competitors in the area. After copulation, the sperm takes between 7-10 minutes to reach the female's bursa.[15] During this time, if the female mates with another male, he will inhibit the sperm of the first male. As a result, mate-guarding is a common behaviour. Carazo et al. (2012) tested whether the beetles could keep a mental tally of potential rivals by presenting male rivals sequentially before a staged mating. They found that the more rivals the male encountered before the copulation, the longer they spent mate-guarding afterwards. Carazo et al. suggest that this is evidence of true numerosity or quantity estimation, and concluded that invertebrates, like the mealworm beetle, share similar core systems of non-verbal, numerical representation with vertebrates.

And last, in terms of learning, not only can mealworm larvae be taught to make certain choices in response to rewards and punishments, but as seen in the common housefly, the learning survives the process of metamorphosis and continues into their adult beetle state (Borsellino et al., 1970). In this study, the beetles who were taught to choose one arm of a maze as a larva could then replicate this choice as an adult (Borsellino et al., 1970). Not only was this learnt behaviour maintained through metamorphosis, but the beetles also showed long-term memory for the learnt behaviour, as the pupate stage alone lasted 17 days.

Environmental needs

The effect of relative humidity on mealworms appears to vary, and their resilience depends largely on the environmental temperature (Ribeiro et al., 2018). The combination of temperature and relative humidity affects both mortality and larval length, and so ensuring mealworms are kept in the right conditions has benefits both for industry, and for the wellbeing of the mealworms, particularly as it is the larval and egg stage that are actually the most sensitive to environmental conditions (Ribeiro et al., 2018).

Mealworms are highly dependent on moisture and will grow most quickly at 90-100% relative humidity. Their growth rate slows at lower levels, and if the atmosphere is too dry the larvae will stop feeding and become inactive in a state of dormancy (Ribeiro et al., 2018). High levels of humidity also introduce contaminants though, such as fungi and mites, which pose challenges for industry, and may introduce conflict when it comes to addressing needs. Rearing temperature also has large and independent effects on growth rate in mealworm larvae, and is critical for production, and potentially for larvae wellbeing (Bjørge et al., 2018).

For optimum wellbeing, growth and survival rates, an optimal temperature of 25-27°C can help buffer the larvae against less-optimal humidity levels (Ribeiro et al., 2018). Ensuring that the larvae can obtain water either from their food or from the atmosphere is also key for them to survive and grow normally. The challenges this poses in terms of managing contaminants, such as fungi, when mass-rearing mealworms, represent important areas for industry to address (Grau et al., 2017). Optimum levels of relative humidity and temperature are also key for oviposition. Humidity is particularly important for this stage to avoid loss of body moisture and subsequent death of the adult (Ribeiro et al., 2018).

As mealworm larvae and adults are negatively phototropic, there is potential for their welfare to suffer if they can not avoid bright light for part of the day. Ensuring the right balance for their wellbeing is an important consideration for production, as larval development can be optimised by ensuring the right balance of light and dark over 24 hours (Ribeiro et al., 2018).

[14] 'Polygynandrous': both males and females have multiple mating partners.

[15] Bursa is a genital chamber in female insects. After mating, the sperm is transferred in a spermatophore, and then released 7-10 minutes later into the female's bursa.

Densities

As with all insect species, studies performed on densities are not necessarily applicable to mass-rearing scales, as even when the densities are scaled up, the effects are not necessarily proportionate. In mealworms, the population densities for larvae negatively influence the number and duration of larval molts[16] (Ribeiro et al., 2018). Crowding may also result in inhibition of the pupation stage, incomplete transformations, slower growth rates due to fewer feeding opportunities, and cannibalism (Ribeiro et al., 2018). In addition, the increased metabolism of the larvae in a crowded population results in a substantial increase in temperature, which can quickly become fatal.

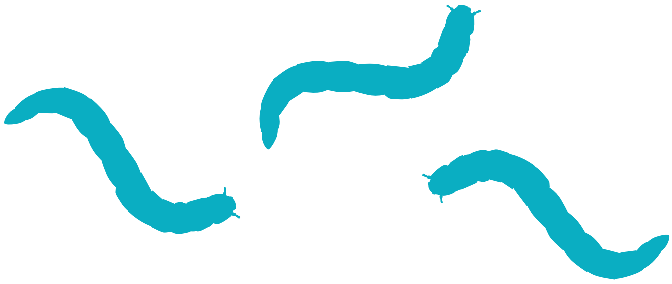
Oxygen concentrations are also important for larvae and can be negatively affected by overcrowding. In low oxygen concentrations, larval mortality and abnormalities are common, and larvae growth rates are impaired (Ribeiro et al., 2018).

Climbing and tunnelling behaviour also increases in overcrowded populations, which is a response to a lack of, or poor quality, of resources and pupation sites (Geden and Axtell, 1987). Providing appropriate and sufficient pupation sites is, therefore, an important element of rearing mealworms if they are harvested at or after pupation, although for feed and food, most mealworms are harvested before they pupate. Nevertheless, providing sufficient and good quality resources to larvae before pupation will remove the need for them to climb and tunnel, which may indicate poor welfare and their needs not being met.

In addition to managing densities, the composition of a mealworm population is also an important concern for industry and mealworm wellbeing. When larvae, who are in different stages or instars, are kept together (pupating larva, and active larvae), this can result in the active larvae cannibalising the pupae (Geden and Axtell, 1987). Overcrowding and poor composition may also interfere with the behavioural and physiological sequences performed by late instar larvae as they prepare to pupate (Geden and Axtell, 1987).

Overcrowding is also detrimental to adults' reproductive output, and studies suggest that a density of 8.4 adults/dm² is optimal (Morales-Ramos et al., 2012). Although, other studies suggest that higher densities of adult beetles are optimum from a reproductive or production perspective and that the beetles are not stressed by this, but adapt their egg-laying according to the density or feed conditions available (Berggreen et al., 2018). Although Berggreen et al.'s statement regarding stress levels appears to be an assumption, rather than based on any evidence.

Cannibalism is a problem at all ages for these mealworm species. Larvae and adults may cannibalise the eggs, and larvae may cannibalise each other (Deruytter et al., 2019). Not only can this have production impacts, as cannibalism can significantly reduce output, but there may also be welfare implications for the individuals being cannibalised, and those performing the act may do so in response to stress-inducing conditions.



Hormone treated mealworms

Some industries (mainly the pet food industry) are currently artificially treating mealworms with juvenile hormones to influence their moulting process (van Huis, 2020a). These hormones cause them to grow beyond their normal length into *'mighty mealies'*. There has so far been no published studies into the potential welfare implications that this hormone treatment may have upon the mealworms.

Handling and slaughter

Once the mealworm larvae reach around 170mg they are sifted out from the frass (insect waste), bedding and food using a mesh sieve (Andersen et al., 2017). Some larvae are kept for reproduction, whereas most are slaughtered. Larvae intended for reproduction tend to be reared with the adult population, which reduces the need for handling adult beetles (Rowe, 2020). Strategies that minimise handling have both production benefits and potential welfare benefits, as individuals may become stressed or injured by routine handling, and handling and sorting are labour intensive (Berggreen et al., 2018). As bold beetles appear to be more resilient to predator stress than shy beetles, as seen in their increased latency to freeze, and their faster speed of recovery (Krams et al., 2014), bolder beetles may be more suited to farming than shyer ones. Moreover, as bold beetles produce more eggs (Monceau et al., 2017), there are potential advantages for utilising personality profiles in insect reproduction, for both production and welfare.

The majority of the mealworms are slaughtered at the larvae stage, and methods include boiling, freezing, and more rarely, freeze-drying (Rowe, 2020). Little has been done to understand the welfare impacts that these methods have. One study looked at the killing method from a nutritional perspective and concluded that freezing was preferable, as it slows down the larvae's metabolism (Adámková et al., 2017). Whether or not this has welfare benefits is unclear.

Can mealworms be farmed humanely?

As with some of the other insect species discussed, the focus of scientific research has been on the ability of these animals to withstand different conditions when rearing and to understand which factors can be manipulated for a better production value. It may be that faster-growing, heavier mealworm larvae are also more likely to have better welfare, but as so little has been done on their behaviour and needs in these situations, it is too early to tell.

Mortality is of course an important factor, and insects do not withstand unfavourable conditions for long. It is, therefore, important from both the mealworms' perspective and from industry's, to understand what constitutes good welfare for these animals.

[16] Larval molts: shedding of the exoskeleton to allow for growth

BANDED, FIELD OR HOUSE CRICKETS

(Gryllades Sigallatus, Acheta Domesticus or Gryllus Assimilis) and the migratory locust (Locusta Migratoria)

The banded cricket, the house cricket, and the field cricket are all approved in the EU for use as livestock feed, and the house cricket is approved for human consumption. It is likely that the banded cricket will also be approved for food once the EFSA opinion has been published. The migratory locust is also approved for human consumption.

WHAT TO LOOK OUT FOR:

- Need for mixed omnivorous diet avoiding use of commercial feeds
- Overcrowding and inadequate diet induced cannibalism
- Chronic stress
- Provision of adequate shelter and coverings
- Sensitivity to disease and viruses
- Natural flying behaviour unsuited for captive and enclosed conditions

Unlike the previous insect species discussed so far, it is the adult form of crickets and locusts that are used as food and feed. Furthermore, crickets and locusts hatch out of the egg as nymphs, which look like small versions of adults, but without wings and full reproductive capacities. As the nymph grows, they shed their exoskeleton in molts, which can take place 8-10 times before they are adults (Hanboonsong and Durst, 2020).

The adult cricket and locust have fully developed wings and the females have ovipositors for egg-laying. Crickets and locusts are often reared in plastic bins, with cardboard materials inside to provide more surface area and a place for females to oviposit (Rowe, 2020). Even the more sophisticated large cricket farms just use cardboard towers.[17] There are usually damp sponges in the containers, to create humidity whilst preventing drowning (Hanboonsong and Durst, 2020).

A female cricket can lay up to 3,000 eggs over her lifetime, but often in production, they are slaughtered before they reach this point (Rowe, 2020). In fact, they are typically slaughtered or sold live as soon as they reach full size at around 7-8 weeks (Hanboonsong and Durst, 2020). Naturally, crickets can live for around 3 to 5 months, depending on conditions. The eggs hatch after two weeks, and the nymphs typically integrate with the larger colony, with some kept for breeding.

A female migratory locust can lay up to 360 eggs in her lifetime, but like with crickets, they are usually slaughtered soon after they mature, and so only the reproductive colony will produce such numbers. Locusts can live for between 2.5 to 5 months, and potentially longer if the conditions are optimal.

Crickets and locusts are becoming popular choices for farming for food and feed as, when they are dried, crickets are composed of 60-75% protein, and 7-20% fat and locusts are composed of 40-60% protein and 10-25% fat (Roos, 2018). The species that are currently approved also have short lifecycles, making them more economically viable compared to other species (van Huis et al., 2013).

BEHAVIOUR OF CRICKETS AND LOCUSTS

Feeding behaviour

Crickets are omnivorous and can consume a large variety of foods, and will scavenge on plant and animal items (Erens et al., 2012). In farms, crickets are typically fed vegetables and chick starter feed, or commercially prepared feed (Hanboonsong and Durst, 2020; Reverberi, 2020). Studies of crickets in laboratory settings have found that they have a longer life span when fed a mixed diet, compared with crickets fed only plants or animal tissues (Erens et al., 2012). The migratory locust is mainly graminivorous (grass-eating), but can eat plants from many species when necessary (Burggren, 2017). They will also feed almost continuously if they can. In farms, locusts are usually fed plant matter, along with commercial cricket feed (Egonyu et al., 2021).

Both locusts and crickets can be cannibalistic, and triggers for this behaviour include overcrowding and inadequate food resources. Some consider the cannibalistic behaviour of crickets to be a way of self-regulating the population (Makkar et al., 2014). Cannibalism does occur naturally, and it is thought to be a trigger for the shift from solitary locusts to the gregarious phase (Guttal et al., 2012).

[17] For example: https://entonation.com/inside-the-largest-edible-cricket-farm-in-the-world/

Social behaviour

The banded, house and field crickets naturally form colonies, and so are adapted to social living. However, a true understanding of natural densities is not known (Erens et al., 2012). Male crickets frequently engage in agonistic contests to gain access to food, establish dominance, and gain access to mate attraction territories (Bertram et al., 2010). The contests are composed of a series of discrete behaviours that increase in aggression and energy expenditure as the fight progresses. During and following a conflict, crickets often perform aggressive songs and body jerks, which are considered to be victory displays (Bertram et al., 2010). In the wild, the social network of crickets is stable across generations, but it is unclear how the social structure is influenced by farming when most are killed before reproducing (Fisher et al., 2016).

Locusts can either be gregarious or solitary, depending on environmental conditions (Lorenz, 2009). In low densities, locusts are typically solitary, acting as individuals. Solitary locusts tend to avoid contact with others, although once numbers rise, the nymphs are forced together, and form larger groups called bands.

These individuals then react more positively to one another and actively aggregate. When the population density reaches a critical density, the banded (flightless) nymphs start marching together (Lorenz, 2009). When resources are poorly distributed, the marching bands remain cohesive and recruit others in their marches. Once in adult form, they continue to be cohesive, forming swarms. Stragglers from swarms will quickly orientate themselves back into the swarm. The gregarious behaviours and physiology are then transmitted to offspring so that it continues throughout generations (Lorenz, 2009). During this transformation, the locust's genes go unchanged, but their behaviour and physiology change considerably, so much so, they were once thought to be two different species (Lorenz, 2009).

Activity

Crickets tend to be more active at dusk and during the night, during which, males make sounds to attract females and will often fight one another (Erens et al., 2012). Crickets may also be active during the day and are capable of flying (Erens et al., 2012). Gregarious locusts are generally active during the day, whereas solitary locust activity peaks at around 10 hours after dusk (Gaten et al., 2012). Migratory locusts can fly thousands of kilometres over land when needed and will perform shorter, local migrations regularly (Lorenz, 2009).

WELFARE IMPLICATIONS FOR CRICKETS AND LOCUSTS

Sentience and cognition

As with other insect species, little has been performed scientifically into the subjective minds of crickets and locusts. Crickets are capable of chronic stress, as a result of the long-term elevation of stress hormones, but whether there is a subjective element of this experience is unclear (Adamo and Baker, 2011; Adamo and McKee, 2017). Nevertheless, chronic stress has considerable negative physiological implications, including reduced weight gain, decreased feeding, and weight loss (Adamo and Baker, 2011).

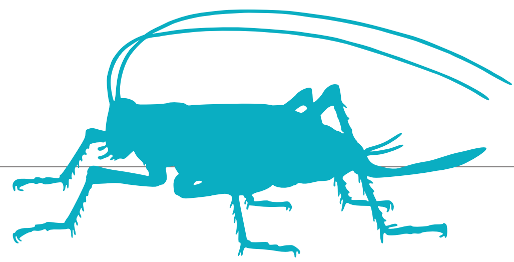
Crickets and locusts have been studied more widely for their cognitive abilities, and cognitive traits such as memory and learning have been identified in several species. Furthermore, studies show that cognitive abilities can be influenced by their welfare. For example, in the house cricket, nymphs who are reared in an enriched environment perform better on memory tasks, compared with those reared in impoverished conditions (Mallory et al., 2016).

Crickets are also capable of spatial learning and can be trained to locate food rewards in a complex maze (Doria et al., 2019). In one study, not only could the female field crickets learn and remember the location of the food, but they also improved with training, reducing the time taken, the number of errors, and the distance travelled to get to the food (Doria et al., 2019). In addition, there was an association between personality and cognitive abilities, as the crickets who spent less time wall-hugging (bold crickets), performed better at the task, compared with those who were prevalent wall-huggers (shy crickets) (Doria et al., 2019).

Migratory locusts can learn to associate different colours with different types of food (protein or carbohydrate-rich), and will use this information to access the nutrients they need (Raubenheimer and Tucker, 1997). They can also do this with odours, again using their learnt knowledge to address nutritional imbalances in their diet (Simpson and White, 1990). Migratory locusts can show excellent individual learning, but despite their often gregarious nature, attempts to identify social learning have failed (Dukas and Simpson, 2009). Locusts do show rapid individual learning though, and can learn a new food after only 20 minutes, and will then show clear preferences for that *'safe'* food when given a choice of the *'safe'* food and a novel food of equal nutritional quality (Dukas and Simpson, 2009).

The house cricket has been shown to perform the cognitive skill of quantitative discrimination. In this study, crickets were presented with locations containing different numbers and types of shelters (Gatto and Carlesso, 2019). The crickets could not only estimate and distinguish between different quantities (2 items versus 3 items), but also distinguished between other relevant features such as width and shape, when deciding upon which location to go to. Features that were not relevant to the crickets, such as the resource's height, were ignored. Instead, they consistently opted for the greater number and greater width (Gatto and Carlesso, 2019).

Similar abilities have been found in locusts, and in one study, locusts were trained to discriminate between colours or odours but were given choices of feed in terms of quantity, rather than a reward or punishment (Behmer et al., 2005). The locusts could perform both associative learning, and also discriminate between large and small amounts, showing a capacity for estimating quantity.



Feeding

Crickets live longer when they are fed a diet of both animal and plant products (Erens et al., 2012), although this does not matter for most of the production process, as crickets are slaughtered long before their natural lifespan has ended. This may, however, have implications for their welfare, particularly as crickets will not survive on inadequate diets. For example, in one study, when house crickets were fed minimally processed food waste and diets comprised mainly of straw, nearly all (>99%) died before reaching a harvestable size (Lundy and Parrella, 2015). The need to feed crickets a balanced diet, rather than just waste streams, can introduce competition for feed that is already being used for vertebrate livestock and questions the efficiency of the industry (Lundy and Parrella, 2015).

As cannibalism is a concern for both crickets and locusts, the quantity and type of food are important. When fed diets restricted in key nutrients, locusts will quickly cannibalise on others to replenish nutrient deficiencies. To what extent this causes suffering is unknown. There are reports of locusts continuing to feed whilst being eaten by another locust, or a predator. The apparent ignorance of being consumed is considered to be evidence that they cannot feel pain, though there are debates on this subject (Bear, 2020; van Huis, 2020a).

Environmental needs

Crickets and locusts prefer warm and humid conditions, but like with other insects, if the temperature and humidity fall outside of their preferred range, their growth and mortality rates are impacted (Hanboonsong and Durst, 2020; Turck et al., 2021).

Crickets are primarily nocturnal and need to hide during the day. Therefore, shelters and covers are important for these animals, to allow them to perform natural behaviours, and to optimise their wellbeing. The shelter needs to account for all individuals in the colony, though, to avoid causing additional fighting and stress (Erens et al., 2012).

The migratory locust naturally migrate over hundreds of kilometres, and so being reared in a small cage significantly impedes their natural behaviour (van Huis, 2020a). Although crickets tend not to fly as much, there are certain occasions and contexts when they are motivated to do so (Erens et al., 2012; van Huis, 2020a). To what extent this impacts their welfare is unclear. In vertebrates, restricting the movement of long-ranging animals is known to impact welfare both physiologically and mentally (Holdgate et al., 2016; Miller et al., 2019).

If we are to use the precautionary principle here, then there is significant potential for the size of the flying area to be a concern, especially for migratory locusts who naturally swarm and migrate vast distances.

Densities

Population density is a key consideration for crickets and locusts. In crickets, population density has significant effects. When kept at high densities, crickets will show suppressed growth and development (Iba et al., 1995). In crowded conditions, they are also more aggressive, which can cause more injuries and cases of cannibalism (Iba et al., 1995; Simpson et al., 2006). Crowding even influences the brain chemistry of crickets, although the implications of this are not yet understood (Delvendahl et al., 2022). The crickets will also become more active, and responsive to tactile, visual and olfactory stimuli when in high-density environments (Delvendahl et al., 2022).

Keeping high densities of male house crickets in a rearing colony can have adverse effects upon their welfare, as increases in fighting behaviour result in injuries, mortalities, and potentially fear and distress (Erens et al., 2012). The energy used in fighting may also negatively affect their longevity. An understanding of optimum male to female ratios is therefore important for farming these animals (Erens et al., 2012).

In farmed systems, locusts are always raised in groups, resulting in them only occurring in the gregarious form, with no solitary individuals being reared (van Huis, 2020a). To some extent, this is a restriction of normal behaviour, as the solitary behaviour cannot be expressed, although whether this is an issue is unclear (Erens et al., 2012). Erens et al. suggest there is a need for more research on the effects of keeping locusts in their gregarious form, and the effects this may have upon their long-term welfare, particularly in regards to the physiological effects that arise. There are some benefits, though, as studies have shown that when migratory locusts are raised in dense populations, they are more resistant to pathogens than solitary locusts are (Erens et al., 2012).

Diseases

Little research has been performed on diseases in crickets and locusts (Eilenberg et al., 2015; Reverberi, 2020). There are, however, several dangerous viruses and bacteria for crickets, which can severely harm or kill them. Although the consensus is that there is little chance of these viruses affecting humans, there are concerns from a welfare perspective, as some viruses can cause severe symptoms such as paralysis, before death (Reverberi, 2020). Crickets are very sensitive to diseases when reared in high densities, and if kept in too high densities, dormant viruses in crickets begin to have adverse effects (Erens et al., 2012).

Handling and slaughter

For harvesting, crickets and locusts have to be moved from the rearing area for killing. This involves some level of handling, whether by human hand or mechanical device. Some North American cricket farmers claim that harvesting under low temperatures helps to calm the insects, making the process more humane (Reverberi, 2020).

As with much of the insect industry, there have been no proper investigations into the welfare considerations of different slaughter methods for crickets and locusts, as most of the focus is upon the nutritional or sensory quality resulting from each killing method (Farina, 2017). As a result, most practices are based upon guesswork when it comes to providing a humane death (Bear, 2019). The Food and Agriculture Organization of the United Nations (FAO) suggests that killing should be done via shredding or freezing (Reverberi, 2020). And in Europe, freezing is the most typical method of slaughter, although shredding and heating are also common (Rowe, 2020). Freeze-drying is usually used to remove the water, and crickets may be freeze-dried live or dead (Rowe, 2020).

Can crickets and locusts be farmed humanely?

Although there has been no research performed on the sentience of crickets and locusts, they do appear to have an array of cognitive skills which hints at their mental complexities. Furthermore, the natural flying behaviour of locusts and crickets may make them unsuited to captive conditions in such enclosed conditions. This may particularly be relevant for the migratory locust, as they naturally travel considerable distances. Whether these animals can be farmed humanely depends partly on whether being restricted from performing instinctive behaviours such as flying cause them distress or not. If it does, then some species, such as the migratory locust, may be unsuited to farming, as the captive environment fails to meet the needs of the reproductive colony. Whereas, some of the cricket species that rarely fly and are comfortable in high densities, may still be suitable, but research into their capacity to feel and suffer is greatly needed.

It is also unclear to what extent the commonly used killing methods have upon the welfare of these animals, and whether they suffer during these processes. Research into their behavioural responses may shed light on this question.

WESTERN HONEY BEE

(Apis Melifera[18]

The Western honey bee is being considered for human consumption in the EU, and potentially as animal feed in the future. In particular, it is the drone brood - larvae, prepupae and pupae - that are currently being proposed as a novel food.

WHAT TO LOOK OUT FOR:

- Sensitivity to pests (verroa mites)
- Lack of scientific knowledge on killing methods

The drone broodstock of honey bees is comprised of males, whose main purpose is to mate with young queens. They are naturally found in beehives during the honey production season, but in many countries, the drone broods are removed from hives to control varroa mites which prefer the drone brood (Jensen et al., 2019. Drone broodstock has a high nutritional value, containing high amounts of protein, fat, vitamins and minerals (Ghosh et al., 2021. Drone larvae are fed by worker bees with honey and pollen and grow in a clean beehive environment in sealed beeswax cells.

Honey bees naturally respond to changes in the ratio of pollen supply and protein demand in the hive and will vary what type of bee is produced accordingly (worker, drone) (Jensen et al., 2019). Drone brood production is dependent on a good pollen supply to meet their protein demand. Drone larvae are more costly for bees to produce and maintain, and so colonies regulate drone production according to food availability and season.

Optimal drone production is dependent on many factors including climate, colony status, and forage availability conditions. The amount of drone broodstock in the colony also affects drone production, and so regularly harvesting them is one way for farmers to ensure that drone production continues (Jensen et al., 2019. Once ready to harvest, farmers often wash the brood combs to remove the larvae or freeze them to allow the comb to be broken up.

Other methods include using liquid nitrogen, or the squeeze method which involves pushing the comb through a sieve to *'juice the larvae'* (Jensen et al., 2019. Most of the harvest methods are also killing methods.

Can honey bees be farmed humanely?

In many ways, the drone larvae are a by-product of honey production and are already being removed to minimise the effect of the varroa mite (Jensen et al., 2019). To produce adequate numbers of drone larvae, the colony may be manipulated, by regularly harvesting the drone brood, ensuring adequate food resources, and optimum temperatures, but these are all commonplace procedures for honey production. As a result, the production of drone larvae for food consumption introduces no new challenges from a welfare perspective that haven't already been reviewed in terms of honey production.

The method for killing the larvae does still need attention though and would need this even if they weren't being used for consumption, as they are still routinely being harvested. As yet, there has been no work performed in regards to the killing methods of drone larvae, despite them being killed to control disease. Therefore, this area needs attention.

[18] As honeybees are already being farmed for the production of honey, and the drone larvae is a by-product, this section differs from the others, as the welfare considerations of honey production are not in question here.

References

Abd El-Hack, M.E., Shafi, M.E., Alghamdi, W.Y., Abdelnour, S.A., Shehata, A.M., Noreldin, A.E., Ashour, E.A., Swelum, A.A., Al-sagan, A.A., Alkhateeb, M., Taha, A.E., Abdel-moneim, A.M.E., Tufarelli, V., Ragni, M., 2020. Black soldier fly (Hermetia illucens) meal as a promising feed ingredient for poultry: A comprehensive review. Agric. 10, 1–31. https://doi.org/10.3390/agriculture10080339

Adámková, A., Adámek, M., Mlček, J., Borkovcová, M., Bednářová, M., Kouřimská, L., Skácel, J., Vítová, E., 2017. Welfare of the mealworm (Tenebrio molitor) breeding with regard to nutrition value and food safety. Potravin. Slovak J. Food Sci. 11, 460–465.

Adamo, S., 2016. Subjective experience in insects: Definitions and other difficulties. Anim. Sentience 1, 1–4. https://doi.org/10.51291/2377-7478.1153

Adamo, S.A., Baker, J.L., 2011. Conserved features of chronic stress across phyla: The effects of long-term stress on behavior and the concentration of the neurohormone octopamine in the cricket, Gryllus texensis. Horm. Behav. 60, 478–483. https://doi.org/10.1016/j.yhbeh.2011.07.015

Adamo, S.A., McKee, R., 2017. Differential effects of predator cues versus activation of fight-or-flight behaviour on reproduction in the cricket Gryllus texensis. Anim. Behav. 134, 1–8. https://doi.org/10.1016/j.anbehav.2017.09.027

Akhtar, Y., Isman, M.B., 2018. Insects as an Alternative Protein Source, Second Edi. ed, Proteins in Food Processing: Second Edition. Elsevier Ltd. https://doi.org/10.1016/B978-0-08-100722-8.00011-5

Andersen, J., Berggreen, I.E., Heckmann, L.L., 2017. Recommendations for Breeding and Holding of Regular Mealworm Recommendations for breeding and holding of regular mealworm, Tenebrio molitor.

Baracchi, D., Baciadonna, L., 2020. Insect sentience and the rise of a new inclusive ethics. Anim. Sentience 5, 1–5. https://doi.org/10.51291/2377-7478.1604

Barron, A.B., Klein, C., 2016. What insects can tell us about the origins of consciousness. Proc. Natl. Acad. Sci. U. S. A. 113, 4900–4908. https://doi.org/10.1073/pnas.1520084113

Bear, C., 2020. Making insects tick: Responsibility, attentiveness and care in edible insect farming. Environ. Plan. E Nat. Sp. 0, 251484862094532. https://doi.org/10.1177/2514848620945321

Bear, C., 2019. Approaching insect death: Understandings and practices of the UK's edible insect farmers. Soc. Anim. 27, 751–768. https://doi.org/10.1163/15685306-00001871

Behmer, S.T., Belt, C.E., Shapiro, M.S., 2005. Variable rewards and discrimination ability in an insect herbivore: What and how does a hungry locust learn? J. Exp. Biol. 208, 3463–3473. https://doi.org/10.1242/jeb.01767

Berggreen, I.E., Offenberg, J., Calis, M., Heckmann, L.H., 2018. Impact of density, reproduction period and age on fecundity of the yellow mealworm Tenebrio molitor (Coleoptera: Tenebrionidae). J. Insects as Food Feed 4, 43–50. https://doi.org/10.3920/JIFF2017.0013

Bertinetti, C., Samayoa, A.C., Hwang, S.Y., 2019. Effects of feeding adults of hermetia illucens (Diptera: Stratiomyidae) on longevity, oviposition, and egg hatchability: Insights into optimizing egg production. J. Insect Sci. 19, 1–7. https://doi.org/10.1093/jisesa/iez001

Bertram, S.M., Rook, V.L.M., Fitzsimmons, L.P., 2010. Strutting their stuff: Victory displays in the spring field cricket, Gryllus veletis. Behaviour 147, 1249–1266. https://doi.org/10.1163/000579510X514535

Bessa, L.W., Pieterse, E., Marais, J., Hoffman, L.C., 2020. Why for feed and not for human consumption? The black soldier fly larvae. Compr. Rev. Food Sci. Food Saf. 19, 2747–2763. https://doi.org/10.1111/1541-4337.12609

Birch, J., 2017. Animal sentience and the precautionary principle. Anim. Sentience 017017, 1–15.

Bjørge, J.D., Overgaard, J., Malte, H., Gianotten, N., Heckmann, L.H., 2018. Role of temperature on growth and metabolic rate in the tenebrionid beetles Alphitobius diaperinus and Tenebrio molitor. J. Insect Physiol. 107, 89–96. https://doi.org/10.1016/j.jinsphys.2018.02.010

Boppré, M., Vane-Wright, R.I., 2019. Welfare Dilemmas Created by Keeping Insects in Captivity, in: The Welfare of Invertebrate Animals. Springer, Cham, pp. 23–67. https://doi.org/10.1007/978-3-030-13947-6_3

Borsellino, A., Pierantoni, R., Schieti-Cavazza, B., 1970. Survival in adult mealworm beetles (Tenebrio molitor) of learning acquired at the larval stage. Nature 225, 963–964. https://doi.org/10.1038/225963a0

Bosch, G., Oonincx, D.G.A.B., Jordan, H.R., Zhang, J., van Loon, J.J.A., van Huis, A., Tomberlin, J.K., 2020. Standardisation of quantitative resource conversion studies with black soldier fly larvae. J. Insects as Food Feed 6, 95–109. https://doi.org/10.3920/jiff2019.0004

Bullock, N., Chapin, E., Evans, A., 2013. The Black Soldier Fly. ENST 698-Environmental Capstone 163–183. https://doi.org/10.7591/cornell/9781501747021.003.0008

Burggren, W.W., 2017. Epigenetics in Insects: Mechanisms, Phenotypes and Ecological and Evolutionary Implications. Adv. In Insect Phys. 53, 1–30. https://doi.org/10.1016/BS.AIIP.2017.04.001

Carazo, P., Fernández-Perea, R., Font, E., 2012. Quantity estimation based on numerical cues in the mealworm beetle (Tenebrio molitor). Front. Psychol. 3, 1–7. https://doi.org/10.3389/fpsyg.2012.00502

Carazo, P., Font, E., Forteza-Behrendt, E., Desfilis, E., 2009. Quantity discrimination in Tenebrio molitor: Evidence of numerosity discrimination in an invertebrate? Anim. Cogn. 12, 463–470. https://doi.org/10.1007/s10071-008-0207-7

Carere, C., Mather, J., 2019. The Welfare of Invertebrate Animals. Springer, Cham.

Chia, S.Y., Tanga, C.M., Khamis, F.M., Mohamed, S.A., Salifu, D., Sevgan, S., Fiaboe, K.K.M., Niassy, S., Van Loon, J.J.A., Dicke, M., Ekesi, S., 2018. Threshold temperatures and thermal requirements of black soldier fly Hermetia illucens: Implications for mass production. PLoS One 13, e0206097. https://doi.org/10.1371/journal.pone.0206097

Čičková, H., Kozánek, M., Moravek, I., Takáč, P., 2012. A Behavioral Method for Separation of House Fly (Diptera : Muscidae). J. Econ. Entomol. 105, 62–66.

Cruse, H., Schilling, M., 2016. No proof for subjective experience in insects. Anim. Sentience 1, 1–4. https://doi.org/10.51291/2377-7478.1146

Delvendahl, N., Rumpold, B.A., Langen, N., 2022. Edible Insects as Food–Insect Welfare and Ethical Aspects from a Consumer Perspective. Insects 13. https://doi.org/10.3390/insects13020121

Deruytter, D., Coudron, C.L., Teerlinck, S., 2019. Influence of crate size, oviposition time, number of adults and cannibalism on the reproduction of Tenebrio molitor. J. Insects as Food Feed 5, 247–255. https://doi.org/10.3920/JIFF2019.0018

Dicke, M., 2018. Insects as feed and the Sustainable Development Goals. J. Insects as Food Feed 4, 147–156. https://doi.org/10.3920/JIFF2018.0003

Doria, M.D., Morand-Ferron, J., Bertram, S.M., 2019. Spatial cognitive performance is linked to thigmotaxis in field crickets. Anim. Behav. 150, 15–25. https://doi.org/10.1016/j.anbehav.2019.01.022

Dörper, A., Veldkamp, T., Dicke, M., 2020. Use of black soldier fly and house fly in feed to promote sustainable poultry production. J. Insects as Food Feed 2050, 1–20. https://doi.org/10.3920/jiff2020.0064

Drnevich, J.M., Papke, R.S., Rauser, C.L., Rutowski, R.L., 2001. Material benefits from multiple mating in female mealworm beetles (Tenebrio molitor L.). J. Insect Behav. 14, 215–230. https://doi.org/10.1023/A:1007889712054

Dukas, R., Simpson, S.J., 2009. Locusts show rapid individual learning but no social learning about food. Anim. Behav. https://doi.org/10.1016/j.anbehav.2009.05.004

Dzepe, D., Nana, P., Fotso, A., Tchuinkam, T., Djouaka, R., 2019. Influence of larval density, substrate moisture content and feedstock ratio on life history traits of black soldier fly larvae. https://doi.org/10.3920/JIFF2019.0034 6, 133–140. https://doi.org/10.3920/JIFF2019.0034

Egonyu, J.P., Subramanian, S., Tanga, C.M., Dubois, T., Ekesi, S., Kelemu, S., 2021. Global overview of locusts as food, feed and other uses. Glob. Food Sec. 31, 100574. https://doi.org/10.1016/j.gfs.2021.100574

Eilenberg, J., Vlak, J.M., Nielsen-LeRoux, C., Cappellozza, S., Jensen, A.B., 2015. Diseases in insects produced for food and feed. J. Insects as Food Feed 1, 87–102. https://doi.org/10.3920/jiff2014.0022

Erens, J., Es van, S., Haverkort, F., Kapsomenou, E., Luijben, A., 2012. A bug's life. Large-scale insect rearing in relation to animal welfare. https://doi.org/10.7748/ns2005.04.19.33.16.c3853

European Commission, 2022. Approval of third insect as a Novel Food [WWW Document]. URL https://ec.europa.eu/food/safety/novel-food/authorisations/approval-insect-novel-food_en (accessed 2.24.22).

European Commission, 2020. EU agricultural outlook for markets, income and environment 2020 - 2030. https://doi.org/10.2762/252413

European Commission, 2019. Specific hygiene rules for insects intended for human consumption [WWW Document]. URL https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/2079-Specific-hygiene-rules-for-insects-intended-for-human-consumption_en (accessed 3.29.22).

Farina, M.F., 2017. How method of killing crickets impact the sensory qualities and physiochemical properties when prepared in a broth. Int. J. Gastron. Food Sci. 8, 19–23. https://doi.org/10.1016/j.ijgfs.2017.02.002

Fisher, D.N., Rodríguez-Muñoz, R., Tregenza, T., 2016. Wild cricket social networks show stability across generations. BMC Evol. Biol. 16, 1–10. https://doi.org/10.1186/s12862-016-0726-9

Francuski, L., Jansen, W., Beukeboom, L.W., 2020. Effect of temperature on egg production in the common housefly. Entomol. Exp. Appl. 168, 513–522. https://doi.org/10.1111/eea.12912

Fukushi, T., 1983. The Role of Learning on the Finding of Food in the Searching Behaviour of the Housefly, Musca domestica (Diptera: Muscidae). Entomol. Gen. 8, 241–250. https://doi.org/10.1127/entom.gen/8/1983/241

Gaten, E., Huston, S.J., Dowse, H.B., Matheson, T., 2012. Solitary and gregarious locusts differ in circadian rhythmicity of a visual output neuron. J. Biol. Rhythms 27, 196–205. https://doi.org/10.1177/0748730412440860

Gatto, E., Carlesso, D., 2019. Spontaneous quantity discrimination in crickets. Ethology 125, 613–619. https://doi.org/10.1111/eth.12912

Geden, C.J., Axtell, R.C., 1987. Factors affecting climbing and tunneling behavior of the lesser mealworm (Coleoptera: Tenebrionidae). J. Econ. Entomol. 80, 1197–1204. https://doi.org/10.1093/jee/80.6.1197

Ghosh, S., Meyer-Rochow, V.B., Jung, C., 2021. Honey bees and their brood: a potentially valuable resource of food, worthy of greater appreciation and scientific attention. J. Ecol. Environ. 45. https://doi.org/10.1186/s41610-021-00212-y

Giannetti, D., Schifani, E., Reggiani, R., Mazzoni, E., Reguzzi, M.C., Castracani, C., Spotti, F.A., Giardina, B., Mori, A., Grasso, D.A., 2022. Do It by Yourself: Larval Locomotion in the Black Soldier Fly Hermetia illucens, with a Novel "Self-Harvesting" Method to Separate Prepupae. Insects 13. https://doi.org/10.3390/insects13020127

Giunti, G., Campolo, O., Laudani, F., Palmeri, V., 2018. Male courtship behaviour and potential for female mate choice in the black soldier fly hermetia illucens L. (Diptera: Stratiomyidae). Entomol. Gen. 38, 29–46. https://doi.org/10.1127/entomologia/2018/0657

Gjerris, M., Gamborg, C., Röcklinsberg, H., 2016. Ethical aspects of insect production for food and feed. J. Insects as Food Feed 2, 101–110. https://doi.org/10.3920/JIFF2015.0097

Grau, T., Vilcinskas, A., Joop, G., 2017. Sustainable farming of the mealworm Tenebrio molitor for the production of food and feed. Zeitschrift fur Naturforsch. - Sect. C J. Biosci. 72, 337–349. https://doi.org/10.1515/znc-2017-0033

Guttal, V., Romanczuk, P., Simpson, S.J., Sword, G.A., Couzin, I.D., 2012. Cannibalism can drive the evolution of behavioural phase polyphenism in locusts. Ecol. Lett. 15, 1158–1166. https://doi.org/10.1111/j.1461-0248.2012.01840.x

Halloran, A., Muenke, C., Vantomme, P., van Huis, A., 2014. Insects in the human food chain: global status and opportunities. Food Chain 4, 103–118. https://doi.org/10.3362/2046-1887.2014.011

Hanboonsong, A., Durst, P., 2020. Guidance on sustainable cricket farming. FAO, Bangkok. https://doi.org/https://doi.org/10.4060/cb2446en

Hassemer, M.J., Borges, M., Withall, D.M., Pickett, J.A., Laumann, R.A., Birkett, M.A., Blassioli-Moraes, M.C., 2019. Development of pull and push–pull systems for management of lesser mealworm, Alphitobius diaperinus, in poultry houses using alarm and aggregation pheromones. Pest Manag. Sci. 75, 1107–1114. https://doi.org/10.1002/ps.5225

Hoc, B., Noël, G., Carpentier, J., Francis, F., Megido, R.C., 2019. Optimization of black soldier fly (Hermetia illucens) artificial reproduction. PLoS One 14, e0216160. https://doi.org/10.1371/journal.pone.0216160

Holdgate, M.R., Meehan, C.L., Hogan, J.N., Miller, L.J., Soltis, J., Andrews, J., Shepherdson, D.J., 2016. Walking behavior of zoo elephants: Associations between GPS-measured daily walking distances and environmental factors, social factors, and welfare indicators. PLoS One 11. https://doi.org/10.1371/JOURNAL.PONE.0150331

Hussein, M., Pillai, V. V., Goddard, J.M., Park, H.G., Kothapalli, K.S., Ross, D.A., Ketterings, Q.M., Brenna, J.T., Milstein, M.B., Marquis, H., Johnson, P.A., Nyrop, J.P., Selvaraj, V., 2017. Sustainable production of housefly (Musca domestica) larvae as a protein-rich feed ingredient by utilizing cattle manure. PLoS One 12, 1–19. https://doi.org/10.1371/journal.pone.0171708

Iba, M., Nagao, T., Urano, A., 1995. Effects of population density on growth, behavior and levels of biogenic amines in the cricket, Gryllus bimaculatus. Zoolog. Sci. 12, 695–702. https://doi.org/10.2108/zsj.12.695

IPIFF, 2019. Ensuring High Standards of Animal Welfare in Insect Production Promoting Animal Welfare Standards for the Sector in Europe.

Jensen, A.B., Evans, J., Jonas-Levi, A., Benjamin, O., Martinez, I., Dahle, B., Roos, N., Lecocq, A., Foley, K., 2019. Standard methods for Apis mellifera brood as human food. J. Apic. Res. https://doi.org/10.1080/00218839.2016.1226606

Jones, B.M., Tomberlin, J.K., Stull, V., 2019. Impact of Larval Competition on Life-History Traits of the Black Soldier Fly (Diptera: Stratiomyidae). Ann. Entomol. Soc. Am. 112, 505–510. https://doi.org/10.1093/aesa/saz014

Jongema, Y., 2017. World list of edible insects. Wageningen Univ. 1–100.

Klein, C., Barron, A.B., 2016. Insects have the capacity for subjective experience. Anim. Sentience 1. https://doi.org/10.51291/2377-7478.1113

Krams, I., Kivleniece, I., Kuusik, A., Krama, T., Freeberg, T.M., Mänd, R., Sivacova, L., Rantala, M.J., Mänd, M., 2014. High Repeatability of Anti-Predator Responses and Resting Metabolic Rate in a Beetle. J. Insect Behav. 27, 57–66. https://doi.org/10.1007/s10905-013-9408-2

Krams, I.A., Krama, T., Moore, F.R., Rantala, M.J., Mänd, R., Mierauskas, P., Mänd, M., 2015. Resource availability as a proxy for terminal investment in a beetle. Oecologia 178, 339–345. https://doi.org/10.1007/s00442-014-3210-5

Lambert, H.S., Elwin, A., D'Cruze, N., 2021. Wouldn't hurt a fly? A review of insect cognition and sentience in relation to their use as food and feed. Appl. Anim. Behav. Sci. 243, 105432. https://doi.org/10.1016/j.applanim.2021.105432

Liu, Z., Najar-Rodriguez, A.J., Morel, P.C.H., Minor, M.A., 2022. Reproduction of Black Soldier Fly (Diptera: Stratiomyidae) under Different Adult Densities and Light Regimes. J. Econ. Entomol. 115, 37–45. https://doi.org/10.1093/jee/toab225

Lorenz, M.W., 2009. Migration and trans-Atlantic flight of locusts. Quat. Int. 196, 4–12. https://doi.org/10.1016/j.quaint.2007.09.038

Lundy, M.E., Parrella, M.P., 2015. Crickets are not a free lunch: Protein capture from scalable organic side-streams via high-density populations of Acheta domesticus. PLoS One 10, e0118785. https://doi.org/10.1371/journal.pone.0118785

Macavei, L.I., Benassi, G., Stoian, V., Maistrello, L., 2020. Optimization of Hermetia illucens (L.) egg laying under different nutrition and light conditions. PLoS One 15, 1–18. https://doi.org/10.1371/journal.pone.0232144

Makkar, H.P.S., Tran, G., Heuzé, V., Ankers, P., 2014. State-of-the-art on use of insects as animal feed. Anim. Feed Sci. Technol. 197, 1–33. https://doi.org/10.1016/J.ANIFEEDSCI.2014.07.008

Mallory, H.S., Howard, A.F., Weiss, M.R., 2016. Timing of environmental enrichment affects memory in the house cricket, Acheta domesticus. PLoS One. https://doi.org/10.1371/journal.pone.0152245

McGuire, T.R., 1984. Learning in three species of diptera: The blow fly Phormia regina, the fruit fly Drosophila melanogaster, and the house fly Musca domestica. Behav. Genet. 14, 479–526. https://doi.org/10.1007/BF01065445

Melgar-Lalanne, G., Hernández-Álvarez, A.J., Salinas-Castro, A., 2019. Edible Insects Processing: Traditional and Innovative Technologies. Compr. Rev. Food Sci. Food Saf. 18, 1166–1191. https://doi.org/10.1111/1541-4337.12463

Miller, L.J., Ivy, J.A., Vicino, G.A., Schork, I.G., 2019. Impacts of natural history and exhibit factors on carnivore welfare. J. Appl. Anim. Welf. Sci. 22, 188–196. https://doi.org/10.1080/10888705.2018.1455582

Miranda, C.., Cammack, J.., Tomberlin, J.., 2020. Mass Production of the Black Soldier Fly, Hermetia illucens (L.), (Diptera: Stratiomyidae) Reared on Three Manure Types. Animals 10, 1–11.

Monceau, K., Dechaume-Moncharmont, F.X., Moreau, J., Lucas, C., Capoduro, R., Motreuil, S., Moret, Y., 2017. Personality, immune response and reproductive success: an appraisal of the pace-of-life syndrome hypothesis. J. Anim. Ecol. 86, 932–942. https://doi.org/10.1111/1365-2656.12684

Morales-Ramos, J.A., Guadalupe Rojas, M., Kay, S., Shapiro-Ilan, D.I., Louis Tedders, W., 2012. Impact of adult weight, density, and age on reproduction of tenebrio molitor (coleoptera: Tenebrionidae). J. Entomol. Sci. 47, 208–220. https://doi.org/10.18474/0749-8004-47.3.208

Morales-Ramos, J.A., Rojas, M.G., Shapiro-Nan, D.I., Tedders, W.L., 2010. Developmental plasticity in Tenebrio molitor (Coleoptera: Tenebrionidae): Analysis of instar variation in number and development time under different diets. J. Entomol. Sci. 45, 75–90. https://doi.org/10.18474/0749-8004-45.2.75

Moruzzo, R., Riccioli, F., Diaz, S.E., Secci, C., Poli, G., Mancini, S., 2021. Mealworm (Tenebrio molitor): Potential and challenges to promote circular economy. Animals 11, 1–16. https://doi.org/10.3390/ani11092568

Niyonsaba, H.H., Hohler, J., Kooistra, J., van der Fels-Klerx, H.J., Meuwissen, M.P.M., 2021. Profitability of insect farms. https://doi.org/10.3920/JIFF2020.0087 7, 923–934. https://doi.org/10.3920/JIFF2020.0087

Pahl, M., Si, A., Zhang, S., 2013. Numerical cognition in bees and other insects. Front. Psychol. 4, 1–9. https://doi.org/10.3389/fpsyg.2013.00162

Park, K., Kim, W., Kim, E., Kwak, K.-W., Choi, J.-Y., Lee, S., Song, M., Kim, S.-H., 2016. Oviposition site preference in Black Soldier Fly, Hermetia illucens (Diptera: Stratiomyidae), in Artificial Rearing System. Int. J. Ind. Entomol. 33, 54–58. https://doi.org/10.7852/ijie.2016.33.2.54

Parodi, A., Van Dijk, K., Van Loon, J.J.A., De Boer, I.J.M., Van Schelt, J., Van Zanten, H.H.E., 2020. Black soldier fly larvae show a stronger preference for manure than for a mass-rearing diet. J. Appl. Entomol. 144, 560–565. https://doi.org/10.1111/jen.12768

Proctor, H.S., Carder, G., Cornish, A., 2013. Searching for Animal Sentience: A Systematic Review of the Scientific Literature. Animals 3, 882–906. https://doi.org/10.3390/ani3030882

Ramos-Elorduy, J., 2009. Anthropo-entomophagy: Cultures, evolution and sustainability. Entomol. Res. 39, 271–288. https://doi.org/10.1111/J.1748-5967.2009.00238.X

Raubenheimer, D., Tucker, D., 1997. Associative learning by locusts: Pairing of visual cues with consumption of protein and carbohydrate. Anim. Behav. 54, 1449–1459. https://doi.org/10.1006/anbe.1997.0542

Ray, S., 1999. Survival of olfactory memory through metamorphosis in the fly Musca domestica. Neurosci. Lett. 259, 37–40. https://doi.org/10.1016/S0304-3940(98)00892-1

RDA, 2018. The Emerging Insect Industry. The Hague.

Renault, D., Hervant, F., Vernon, P., 2003. Effect of food shortage and temperature on oxygen consumption in the lesser mealworm, Alphitobius diaperinus (Panzer) (Coleoptera: Tenebrionidae). Physiol. Entomol. 28, 261–267. https://doi.org/10.1111/j.1365-3032.2003.00338.x

Reverberi, M., 2020. Edible insects: cricket farming and processing as an emerging market. J. Insects as Food Feed 6, 211–220. https://doi.org/10.3920/jiff2019.0052

Rho, M.S., Lee, K.P., 2022. Behavioural and physiological regulation of protein and carbohydrates in mealworm larvae: A geometric analysis. J. Insect Physiol. 136, 104329. https://doi.org/10.1016/j.jinsphys.2021.104329

Ribeiro, N., Abelho, M., Costa, R., 2018. A review of the scientific literature for optimal conditions for mass rearing tenebrio molitor (Coleoptera: Tenebrionidae). J. Entomol. Sci. 53, 434–454. https://doi.org/10.18474/JES17-67.1

Roos, N., 2018. Insects and human nutrition, in: Halloran, R., Vantomme, F., Roos, N. (Eds.), Edible Insects in Sustainable Food Systems. Springer International Publishing, pp. 83–91.

Rowe, A., 2020. Insects raised for food and feed — global scale, practices, and policy — Rethink Priorities.

Rumpold, B.A., Schlüter, O.K., 2013. Potential and challenges of insects as an innovative source for food and feed production. Innov. Food Sci. Emerg. Technol. 17, 1–11. https://doi.org/10.1016/j.ifset.2012.11.005

Sheppard, D.C., Tomberlin, J.K., Joyce, J.A., Kiser, B.C., Sumner, S.M., 2002. Rearing Methods for the Black Soldier Fly (Diptera: Stratiomyidae). J. Med. Entomol. 39, 695–698. https://doi.org/10.1603/0022-2585-39.4.695

Shishkov, O., Hu, D.L., 2020. Synchronizing pile formation of black soldier fly larvae. Eur. Phys. J. Spec. Top. 229, 2779–2789. https://doi.org/10.1140/epjst/e2020-900264-y

Shishkov, O., Hu, M., Johnson, C., Hu, D.L., 2019a. Black soldier fly larvae feed by forming a fountain around food. J. R. Soc. Interface 16. https://doi.org/10.1098/rsif.2018.0735

Shishkov, O., Trebuchon, J., Yunker, P.J., Franklin, S., Hu, D.L., 2019b. Black soldier fly larvae rearrange under compression. Integr. Comp. Biol. 59, 1646–1652. https://doi.org/10.1093/icb/icz133

Simpson, S.J., Sword, G.A., Lorch, P.D., Couzin, I.D., 2006. Cannibal crickets on a forced march for protein and salt. Proc. Natl. Acad. Sci. U. S. A. 103, 4152–4156. https://doi.org/10.1073/pnas.0508915103

Simpson, S.J., White, P.R., 1990. Associative learning and locust feeding: evidence for a "learned hunger" for protein. Anim. Behav. 40, 506–513. https://doi.org/10.1016/S0003-3472(05)80531-7

Sogari, G., Menozzi, D., Mora, C., 2019. The food neophobia scale and young adults' intention to eat insect products. Int. J. Consum. Stud. 43, 68–76. https://doi.org/10.1111/IJCS.12485

Tomberlin, J.K., Sheppard, D.C., 2002. Factors influencing mating and oviposition of black soldier flies (Diptera: Stratiomyidae) in a colony. J. Entomol. Sci. 37, 345–352. https://doi.org/10.18474/0749-8004-37.4.345

Turck, D., Castenmiller, J., De Henauw, S., Hirsch-Ernst, K.I., Kearney, J., Maciuk, A., Mangelsdorf, I., McArdle, H.J., Naska, A., Pelaez, C., Pentieva, K., Siani, A., Thies, F., Tsabouri, S., Vinceti, M., Cubadda, F., Frenzel, T., Heinonen, M., Marchelli, R., Neuhäuser-Berthold, M., Poulsen, M., Maradona, M.P., Schlatter, J.R., van Loveren, H., Azzollini, D., Knutsen, H.K., 2021. Safety of frozen and dried formulations from migratory locust (Locusta migratoria) as a Novel food pursuant to Regulation (EU) 2015/2283. EFSA J. 19. https://doi.org/10.2903/j.efsa.2021.6667

van Broekhoven, S., Oonincx, D.G.A.B., van Huis, A., van Loon, J.J.A., 2015. Growth performance and feed conversion efficiency of three edible mealworm species (Coleoptera: Tenebrionidae) on diets composed of organic by-products. J. Insect Physiol. 73, 1–10. https://doi.org/10.1016/j.jinsphys.2014.12.005

van Huis, A., 2020a. Welfare of farmed insects. J. Insects as Food Feed 1–12. https://doi.org/10.3920/jiff2020.0061

van Huis, A., 2020b. Insects to Feed the World 2020 Virtual Conference, in: Insects to Feed the World 2020 Virtual Conference. Journal of Insect as Food and Feed, p. Supplement 1.

van Huis, A., Oonincx, D.G.A.B., Rojo, S., Tomberlin, J.K., 2020. Insects as feed: house fly or black soldier fly? J. Insects as Food Feed 6, 221–229. https://doi.org/10.3920/JIFF2020.X003

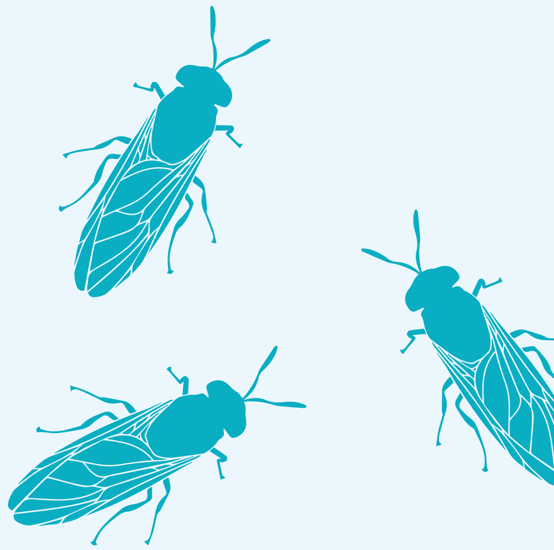
van Huis, A., Van Itterbeeck, J., H, K., Mertens, E., Halloran, A., Muir, G., Vantomme, P., 2013. Edible insects: Future prospects for food and feed security. Rome.

Weaver, D.K., McFarlane, J.E., Alli, I., 1989. Aggregation in yellow mealworms, Tenebrio molitor L. (Coleoptera: Tenebrionidae) larvae - II. Observations and Analyses of Behavioral Parameters in Aggregation. J. Chem. Ecol. 15, 1605–1615. https://doi.org/10.1007/BF01012387

Wilson, T.H., Miner, F.D., 1969. Influence of Temperature on Development of the Lesser Mealworm , Alphitobius diaperinus. J. Kansas Entomol. Soc. 42, 294–303.

Yang, S., 2017. Intensive Black Soldier Fly Farming – SymtonTM Black Soldier Fly [WWW Document]. URL https://symtonbsf.com/blogs/blog/intensive-black-soldier-fly-farming (accessed 3.21.22).

Yen, A.L., 2009. Edible insects: Traditional knowledge or western phobia? **Entomol. Res. 39, 289–298.** https://doi.org/10.1111/j.1748-5967.2009.00239.x



Act4AnimalsEU
eurogroupforanimals
eurogroup-for-animals
eurogroupforanimals

EUROGROUP FOR ANIMALS

EUROGROUP FOR ANIMALS

Rue Ducale 29 –1000 Brussels, Belgium
+32 (0)2 740 08 20

info@eurogroupforanimals.org
eurogroupforanimals.org

© Eurogroup for Animals, 2022

Published by Eurogroup for Animals in July 2022
Authors: Dr Helen Lambert, foreword by Jacopo Moccia
Foreword contributors: Camilla Björkbom
Editor: Marie Cochet
Design: Blush design agency

All pictures' copyrights belong to Eurogroup for Animals, are free of rights or accredited to their owner.

With funding received from the Effective Altruism Funds program