Insects as a sustainable protein source

Potential and challenges

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Abstract

As part of the NewFoodSystems project "Pr:Ins", this study examined the production and marketing of mealworm beetle larvae (*Tenebrio molitor* L.; Coleoptera: Tenebrionidae; "mealworms") as an alternative protein source in terms of quality, sustainability, and consumer acceptance. The research findings reveal promising avenues for further development of this species as a protein source. Mealworm beetle larvae have a favorable nutritional profile with a high protein content, can be produced in an environmentally friendly way using sustainable production methods (e.g., including the use of by-products), and are generally accepted by about 45% of consumers. Various by-products from food and feed production could be used as feed for mealworms, which is beneficial from an environmental perspective, but also represents the biggest cost driver. Other key challenges include optimizing production processes and processing technologies, dealing with potential safety risks, and developing marketing strategies tailored to specific target groups. Future research and development efforts should focus on these aspects to fully unlock the potential of mealworm beetle larvae as an innovative protein source.

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Introduction

With the world population expected to grow to approximately 9.7 billion by 2050, food production will need to increase by around 70% [1]. The effects of climate change are also putting additional pressure on global food security. Thus, the food sector must face the challenge of reducing its environmental impact while simultaneously increasing the amount of food produced for the global market. Finding alternative food and protein sources with lower environmental impacts is therefore a key component in addressing this challenge.

There is currently much discussion about using insects as food and feed as part of a potential solution to global food security challenges. Insect farming not only provides a source of protein but also enables a circular use of materials through the utilization of by-products from food and feed production – provided that existing animal feed regulations are respected [2]. While approximately 2,100 edible insect species are known worldwide, only a few have been approved in the EU as novel foods: the mealworm beetle *(Tenebrio molitor*, Coleoptera: Tenebrionidae, in the larval stage ("yellow mealworm"), the migratory locust *(Locusta migratoria*, Orthoptera: Acrididae), the house cricket (*Acheta domesticus*, Orthoptera: Gryllidae) and larvae of the litter beetle *(Alphitobius diaperinus*, Coleoptera: Tenebrionidae, "buffalo worm") [3]. The production of insect protein involves successive processing steps, from rearing to final processing (◆ Figure 1). Feed preparation includes the production and transport of feed materials as well as conditioning them into a finished substrate. The insects are reared in climate-controlled rooms and the process is divided into the steps of rearing young larvae, fattening, and reproduction. In addition to the steps outlined here (drying, milling, de-fatting, and protein extraction), other processes such as extrusion may also be used in further processing.

For insects to become successfully established on the market as food, knowledge gaps about sustainability, economic viability, consumer acceptance, quality, and safety must be addressed. The aim of the NewFoodSystems project "Pr:Ins – Holistic evaluation of alternative protein sources with special consideration of insects" is therefore to expand knowledge in these areas. Within three sub-projects, each with a distinct research focus, insect-based products – with a focus on mealworm beetle larvae – are analyzed as sustainable and innovative food sources. This three-pronged approach makes it possible to identify how

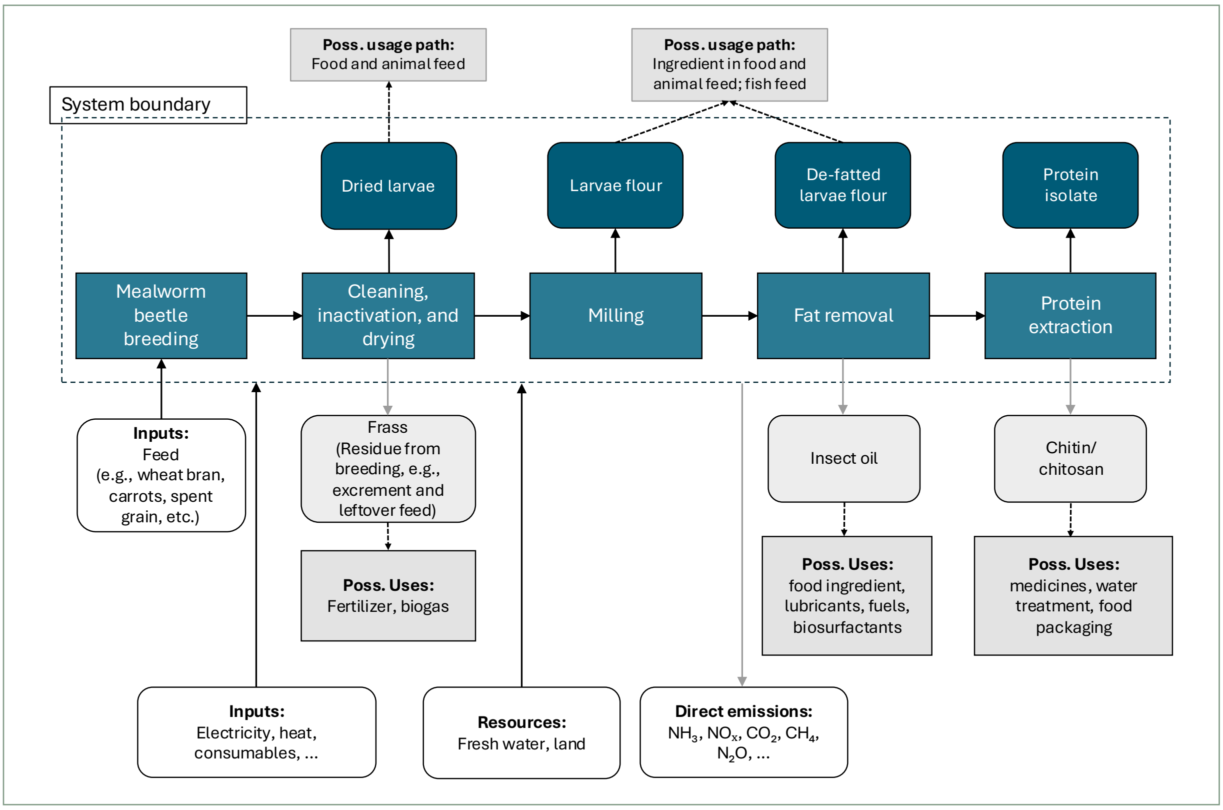

Fig. 1: **System boundaries and process steps in the production of mealworm beetle larvae with the associated inputs, resources, and direct emissions**
The diagram shows the main process steps from the rearing of larvae to protein extraction, as well as the intermediate products produced at each stage.

aspects covered by each sub-project are interlinked and how they influence each other (◆ Figure 2). This article presents the key aspects of quality and safety (sub-project 3), sustainability (sub-project 1), and consumer acceptance (sub-project 2), and illustrates their interrelations.

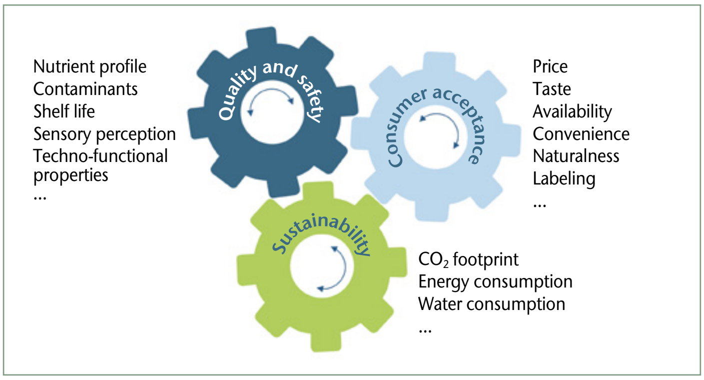

Fig. 2: **Diagram outlining the three sub-projects in the holistic evaluation of mealworm production and mealworm-based products, showing the key parameters examined in each one**

Quality and safety

Nutrient profile and nutritional quality

Generally speaking, the nutritional quality of insects as a food tends to be high. However, species specific differences and the effects of processing are so significant, such that it is not possible to make general statements about the nutritional quality of insects as a whole. Even within a single species, nutrient composition and other quality-determining characteristics can vary considerably. Important factors that influence this variation include feed and its nutritional quality, rearing conditions, and the age or stage (instar) at which the larvae are harvested, as has been demonstrated in our own, as well as other studies (◆ Figure 3).

Fresh (i.e., undried) mealworm beetle larvae typically contain 11–30% crude protein, 6–23% fat, 56–71% water, approximately 1% ash, and approximately 5% other components [9]. With a residual moisture content of approximately 1–3%, dried mealworm beetle larvae and mealworm powders contain approximately 24–55% crude protein, 28–49% fat, 3% ash, and approximately 10% other components. Protein concentrates are made via multi-step processes (◆ Figure 1) and contain up to 80% protein, depending on the processing method used [10]. Protein-rich feed can often lead

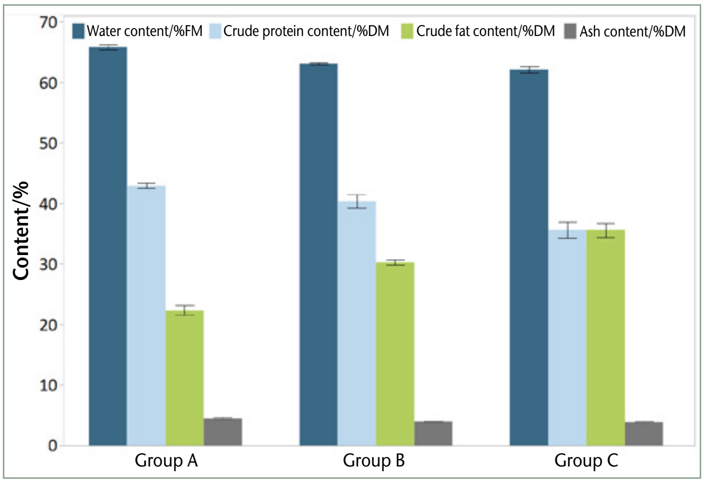

Fig. 3: **Example composition of mealworm beetle larvae from our own feeding study, in which feed and harvest weight were varied**
Group A: Wheat bran, harvest weight 80 mg; Group B: Beet pulp flakes + dried distillers grains with solubles, harvest weight 80 mg; Group C: Wheat bran + rice bran + apple pomace, harvest weight 100 mg
Crude protein and crude fat content are based on dry matter (DM); water content and harvest weight are based on fresh matter (FM). Crude protein was determined using the Kjeldahl method [4] with a conversion factor 4.76 [5], crude fat was determined with the Weibull-Berntrop method [6, 7], water content was determined gravimetrically and ash content was determined after incineration [8]. Mean values ± standard deviations of n = 5 biological replicates are given. (unpublished data)

to a higher protein content, however the protein source also plays an important role [11]. The protein content decreases as the larvae age or stage increases. For example, in our own feeding studies, an increase in weight from 80 mg to 100 mg resulted in a decrease in protein content of around 10% (unpublished data).
The protein content of food is often determined using the Kjeldahl method, in which the protein content is calculated by multiplying the nitrogen content by a conversion factor. The EU Food Information to Consumers Regulation (Regulation [EU] No. 1169/2011) stipulates a conversion factor of 6.25. In the case of insects, this conversion factor leads to an overestimation of the protein content due to the high content of non-protein nitrogen from chitin. For mealworm beetle larvae, the factors 4.76 [5] and 5.33 [12] have been proposed as alternatives, but neither of these factors is currently used as standard. Therefore, it must be assumed that at present, much of the available data overestimates the actual protein content of insects by around 20%.
The digestibility of the protein in mealworm beetle larvae and mealworm powder is roughly equivalent to that of other animal protein sources, such as meat or fish [13]. Studies on the influence of processing, in particular heating steps, cooking methods or extrusion, are scarce and come to different conclusions, indicating a need for further research in this area. The high protein quality of mealworms also results from their favorable amino acid profile, which contains all essential amino acids. The sulfur-containing amino acids cysteine and methionine are limiting in mealworm beetle larvae, whereas lysine (which is limiting in wheat, for example), is non-problematic [14]. In our own, as yet unpublished work, feed and larval weight had little effect on amino acid profiles, which is consistent with observations in the literature [15].
The fat content of mealworm beetle larvae increases with the number of larval stages and can reach up to 22% in fresh mass or 50% in dry mass, with values around 35% being typical [9]. In our own, as yet unpublished study, it was possible to rear larvae with significantly lower fat content – 14% fat in dry matter – through targeted feeding and early harvesting. In terms of the fatty acid profile of mealworm beetle larvae, they generally have a high level of unsaturated fatty acids, especially oleic acid and α-linolenic acid, which comprise about 45% and about 20% of total fatty acids, respectively [16]. Whereas the amino acid profile of mealworm beetle larvae is generally stable and does not depend on their feed, the fatty acid profile can be influenced by different types of feed. For example, adding flax or chia seeds to the feed reduced the ω6:ω3 ratio in mealworm beetle larvae (including their gut contents) from 50 to 3–6, which is beneficial for human nutrition [17].
Since the consumption of insects does not contribute significantly to carbohydrate intake, carbohydrates will not be discussed in any further detail here. However, chitin is worth mentioning, as it accounts for approximately 5% of the dry matter in dried mealworm beetle larvae. Literature indicates that chitin, which is largely indigestible, has positive effects on intestinal health; on the other hand, possible negative impacts on protein digestibility and mineral bioavailability are currently being discussed [18].
Finally, it is important to note that residual feed in the intestines of the larvae can contribute to their nutrient profile [19], and must be taken into account when interpreting the results of relevant studies. However, when used for human consumption, the insects must be fasted for at least 24 hours prior to sacrifice in order to empty their intestines [20], meaning that any potential increase in nutrient levels due to feed residues in the intestines loses relevance in practice.

Sensory properties and processing

The smell and taste of dried mealworm beetle larvae or mealworm powder is spicy/umami, nutty, oily, and “animal-like” with a distinctive aftertaste [21]. As with other foods, processing methods, such as drying, significantly affect the sensory properties of insect-based products. The influence of feed on these properties cannot be excluded and is currently being investigated as part of the “Pr:Ins” project. The characteristic flavors and the effects of insect powder on, for example baking properties, limit the potential applications in food products to some extent. Acceptable applications from a sensory perspective, as well as feasible in terms of techno-functionality include 10–20% mealworm powder in cookies and crackers and 5–10% mealworm powder in wheat bread [22]. In our own, as yet unpublished work, a 30% proportion of blanched mealworm beetle larvae in savory snack balls yielded good results. Adding mealworm beetle larvae to plant-based meat substitutes can even increase consumer acceptance of these products [23]. However, because differences in texture, 5–10% mealworm powder was determined to be the upper acceptability limit for various meat-based sausage products [24]. The extent to which different processing methods can improve the functionality of mealworm powder and protein-rich extracts is currently the subject of research [25], and is also being investigated within the "Pr:Ins" project.

Safety aspects

Mealworm beetle larvae are generally microbiologically safe after they have been appropriately heat-treated. Without a prior heating step, the potential hazards are similar to those of other animal protein sources [26]. Since one of the commonly cited advantages of insects as food is that they can be raised on by-products, there is a need to consider the possible transfer of contaminants from feed to the product. Several studies have shown that there is no accumulation of mycotoxins in mealworm beetle larvae [27]. However, the accumulation of heavy metals could pose a problem [28]. For example, in our own feeding study, feeding rice bran led to an accumulation of arsenic (data not yet published). However, enriching the substrate with zinc reduced cadmium levels in mealworm beetle larvae [29].

One of the main safety concerns associated with eating insects is their allergenic potential. For those with allergies to dust mites and crustaceans, the possibility of allergy cross-reactivity could be a major barrier to consumption. Cross-reactivity can be caused by a number of proteins, including tropomyosin and arginine kinase [30]. The extent to which processing methods can alter the allergenicity of insects is currently being researched. Heat treatment has been shown to partially reduce allergenicity [31].

Feed for mealworm beetle larvae primarily consists of cereal products. Since substrate residues may adhere to the skin or be present in the intestines of the larvae, traces of gluten cannot be ruled out even in processed mealworm beetle larvae [21]. However, mealworm beetle larvae also thrive on many gluten-free substrates, meaning that gluten-free mealworm-based products can also be produced.

Sustainability evaluation: Environmental footprint and potential for optimization of mealworm production

Environmental footprint of mealworm protein from pilot to industrial scale

The key production steps outlined above – from feed provision and breeding to protein extraction – form the technical basis for industrial mealworm production. The breeding and processing facilities that are currently in operation range, in terms of their technological maturity and production capacity, from facilities in the experimental development stage to market-ready industrial facilities. Laboratory-based facilities and pilot plants often operate manually and on a limited production scale, whereas industrial production systems are typically more automated and efficient.

The scientific literature on the sustainability of mealworm breeding and processing is limited. Currently, there are only three studies available that are based on primary plant data from market-ready production facilities with low to medium production capacity [32–34]. The remaining six available studies base their analyses on this primary data and/or combine it with experimental data and results from feeding studies. The studies shed light on fundamental aspects of mealworm production and processing in specific regions, but do not provide comprehensive environmental assessments as they only address individual environmental impact categories. Most of the studies analyze the potential impact on climate change, reporting values for the production of fresh mealworm beetle larvae ranging from 1.0 to 4.6 kg CO_2 equivalents per kilogram [33, 35–37]. This wide range is due to differences in feed composition, energy sources, and production methods. The most significant environmental impacts occur in feed production and energy consumption during breeding [32, 34, 36]. These two factors typically account for up to 50% of total greenhouse gas emissions (GHG emissions) in the rearing of mealworm beetle larvae. Other factors such as wastewater and other waste, as well as the processing and finishing of the fattened mealworm beetle larvae, generally contribute to a much lesser extent to overall emissions. Most of the energy consumption comes from heating the breeding facilities, while emissions from feed production come from cultivating crops, transportation, and the use of fertilizers. The energy mix in the electricity supply has an impact on GHG emissions, with regions using renewable energy or nuclear power generating significantly lower emissions than those using fossil fuels [36].

In order to improve the available data and close gaps in knowledge, primary data from various insect farms and processors in Europe were collected as part of the "Pr:Ins" research project. The goal here was to comprehensively analyze European mealworm production and its environmental potential with a view to integrating it into future food systems. The production data obtained were used to analyze the breeding and processing of mealworm beetle larvae in both pilot industrial facilities and planned industrial facilities. The results showed significant differences between the facilities, depending on factors such as feed type, energy source, degree of automation, and geographical location. Pilot facilities often had a greater environmental impact than larger industrial facilities. This potential for improvement was also evident in the calculation of planning data for an industrial facility belonging to Alpha-Protein GmbH (Bruchsal, Germany), which provided its data for evaluation. Here, production optimizations in upscaling led to environmental impact improvements of up to 72%. The climate change results for the production of fresh mealworm beetle larvae at Alpha-Protein GmbH's planned industrial facility are at the lower end of the range reported in the literature. Here, feed provision accounts for approximately 22% of the climate change impact, fattening accounts for approximately 48%, and processing accounts for approximately 16% (◆ Figure 4). The feed types analyzed were brewer's yeast, stale bread, lignocellulose, and wheat bran. The main contribution to greenhouse gas emissions comes from the wheat bran, or rather from the proportional impact from wheat cultivation and processing that was allocated to it. In fattening and processing, the main contribution comes from the energy used.

Areas for potential optimization of mealworm production

The environmental footprint of mealworm production is primarily determined by how the feed is produced, the energy sources used, and the energy required for fattening, with transportation, processing, and infrastructure playing only a secondary role.

The choice of feed has an impact on both the environmental impact associated with feed production and key breeding parameters such as feed conversion ratio (FCR), survival rate, and duration

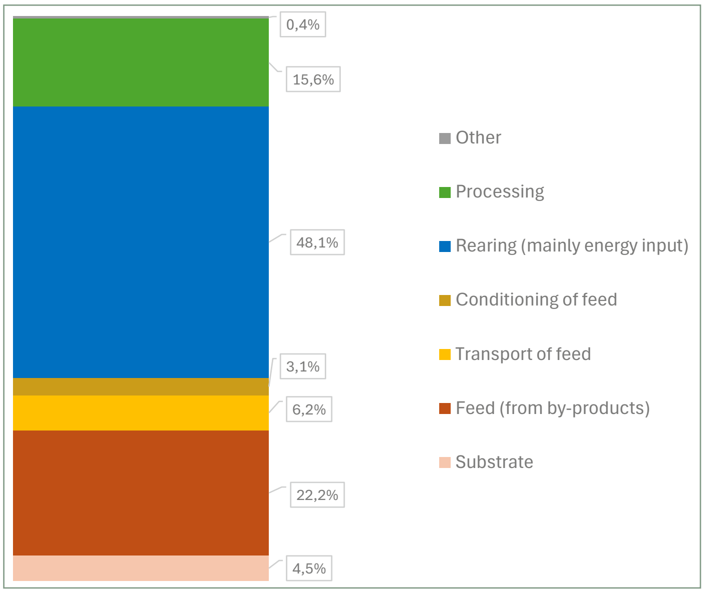

Fig. 4: **Analysis of the contribution made by each process step in the production of mealworm powder to the greenhouse gas emissions of Alpha-Protein's planned industrial facility** (unpublished data)

of rearing. A low FCR combined with a high survival rate optimizes resource utilization and minimizes losses. Supplementary primary feedstuffs such as carrots can shorten the rearing period and increase survival rates. By-products such as wheat bran, brewer's yeast, and stale bread can be a cost-effective and environmentally friendly alternative to primary feedstuffs and help close cycles, making resource utilization more efficient. Studies by the German Federal Research Institute of Nutrition and Food and others have shown that, compared to other insect species such as the black soldier fly, mealworm beetle larvae are more physiologically sensitive to the composition and quality of by-product streams. A suboptimal feed substrate composition leads to a significant reduction in larval survival rates, which in turn results in increased resource input and a less favorable environmental footprint. In addition, using by-products for this purpose could potentially be in competition with already established uses in other sectors. By-products such as grain bran, fruit and vegetable waste, and oil meal are now frequently used in animal feed, biogas production, or as raw materials in the chemical industry. Redirecting these resources to insect production could disrupt existing value chains and potentially increase pressure on primary raw materials if by-products become scarcer as a result. However, if the consumption of other animal-based foods declines in the future, the by-products that become available could be used for insect farming.

The amount of electricity required to maintain optimal breeding conditions is the second largest factor influencing the environmental footprint of mealworm production. Switching to renewable energies could therefore be a very effective way to reduce emissions. Local breeding and utilizing locally available resources could also shorten transportation routes and strengthen local economic cycles.

The example of Alpha-Protein GmbH shows that upscaling from pilot facilities to industrial facilities leads to a reduction in environmental impact, made possible by optimized resource utilization, the use of advanced technologies, and improved production processes. In this way, economies of scale are harnessed to further reduce energy consumption and the resulting emissions per production unit, thereby increasing the sustainability of the entire value chain.

Another area for potential optimization is the possible utilization of by-products from mealworm production. The larval excrement and food residues from fattening (frass) could be used as high-quality fertilizer. This reduces the need for conventional fertilizers and consequently lowers the emissions generated by their production. This means that in the future, mealworm production could form an important part of a resource-efficient food system, as well as being a significant source of protein.

Consumer acceptance

Barriers to acceptance and market potential

Although insects are consumed daily or as part of traditional dishes by more than two billion people worldwide, they are considered novel foods in Western countries (e.g., in the EU) and their consumption is regarded as unusual. A lack of consumer acceptance and willingness to integrate insects into their diets are considered the main challenges for establishing and developing a market. As a result, insects have so far been used primarily as animal feed. Key barriers to consumer acceptance include feelings of disgust and food neophobia, as well as concerns about quality and safety [38, 39]. Other factors not attributable to consumers like product- and market-related factors also play a role in further hindering increased consumption, such as the limited availability of insect-based foods on the market and high prices. Therefore, companies in this sector continue to perform pioneers work in striving to build a market for insects, despite some of them having been working towards this goal for many years. In light of this situation, this article aims to provide a concise overview of the latest findings from consumer research on insect-based foods and their market potential. It draws on a range of already published data from expert interviews, focus group discussions with consumers, consumer surveys, and a literature review [40–43], summarizing their key findings.

Despite the documented barriers to acceptance of eating insects, German society is not homogeneous. There is a significant group of consumers who are fundamentally open to insect-based foods. Our own study results indicate that, out of over 18,000 respondents, almost 45% can imagine themselves eating insects [41]. Of these, between 30% and 40% have already eaten insects and rate this experience as predominantly positive. Both of these factors – a fundamental openness to insects and positive taste experiences – are prerequisites for further market establishment, which makes this an important target group. It has been observed that people who can generally imagine consuming insects often experience feelings of uncertainty and inner conflict (curiosity/interest vs. disgust) when faced with the actual situation of buying or consuming them. Detailed knowledge of the target groups' desires and needs, along with tailored marketing tools, is required to counteract this ambivalence. The following sections present the results and approaches for this.

Product manufacturing and labeling

One factor that can be adjusted to increase consumer acceptance is product development and labeling. Whole insects, whether sold individually or as a visible component of processed foods, are very difficult to market due to the barrier of disgust, and will only appeal to a marginal consumer group in the foreseeable future. Studies from Europe and the US have documented greater openness toward the use of insects as an invisible ingredient (e.g., powder) in processed foods [44].

Insects could potentially be used as an ingredient in a wide range of products across different product categories, but it is important to identify the products that will be most widely accepted. These are primarily products that Western consumers are familiar with in terms of appearance and taste. The snack sector appears to be a particularly promising sector in this regard. For example, in a choice experiment, insect-based crackers had higher rates of acceptance and intention to purchase than falafel-like balls [41]. Crackers, along with other snacks such as bars, benefit from the ongoing convenience trend and the fact that these products can be taken anywhere and eaten anytime. At the same time, because insects contain high-quality proteins and fatty acids, they are attracting consumers interested in protein supplements, sports nutrition, and dietary supplements [45]. Targeting these specific interests, for example by labeling products as "high protein", will enable producers to benefit from consumers' greater willingness to pay, which in turn will cover higher production costs.

To enable consumers to make an informed decision for or against purchasing an insect-based product, clear insect-labeling on the front of product packaging is necessary. Our own consumer study investigating the expectations and preferences for such labeling indicated that consumers would prefer subtle but clear labeling, for example in the form of a standardized label [43]. Furthermore, this study indicated that when balancing the informational impact of such a label against its marketing impact, a general description such as "with protein from insects" is favored over specifying the particular insect species (e.g., "with protein from mealworms"). Highlighting the protein content rather than, for example, insect powder, is particularly well-received by consumers.

Communicating with consumers and product tastings

To strengthen consumer acceptance and ensure the successful marketing of insect-based products, the development of targeted consumer communication is needed. Many producers particularly emphasize the benefits of insects in terms of environmental sustainability and nutritional value. This type of information has been shown to improve consumers' attitudes toward insect-based foods and increase their willingness to buy or try them [46–48]. The results from our own study further indicate that incorporating and emphasizing the aspect of naturalness is relevant for consumer decision-making [41]. Naturalness is also associated with good taste and health benefits, both of which are hedonistic product characteristics. Producers could take this into account in product development by using simple and natural ingredients, keeping ingredient lists short, and avoiding additives and preservatives. This approach addresses growing consumer skepticism toward highly-processed foods and aligns with the increasing importance of clean labeling [49]. In the long term, emphasizing naturalness could potentially serve as a relevant differentiating feature, helping insect-based products to stand out among other alternative products, including vegan and vegetarian products.

Targeted communication is also needed to address consumers' quality and safety concerns. Our study results have shown that this can be achieved through independent product validation by trustworthy institutions. For skeptical and inexperienced consumers in particular, such objective tests, which would be communicated via logo or labels on product packaging, could provide an important basis for decision-making.

While providing information about the benefits of insect consumption and highlighting the unique selling points (USPs) of insect-based foods is important, tastings also play a crucial role in increasing consumer acceptance. Studies have shown that tastings have a positive effect on consumers' attitudes toward entomophagy and increase their intention to eat insect-based foods again [50, 51]. Tastings offer consumers a no-obligation, low-threshold opportunity to gather their own sensory experiences. Another benefit of tastings is that the time between receiving information and consuming the product is very short, which means that information is directly linked to the taste experience and is absorbed more effectively. Unlike eating in private, tasting in public spaces also has a social component. By allowing others to observe them while tasting, people lose the feeling that eating insects is something abnormal. This can reduce feelings of disgust and trigger a kind of snowball effect. Tastings can be pivotal, especially when consumers are trying insects for the first time, as negative experiences can lead to a permanent rejection of insect-based foods, while positive experiences can create long-term openness to them.

Outlook

Producing and marketing mealworm beetle larvae as food presents complex but solvable challenges in the areas of quality and safety, sustainability, and consumer acceptance.

In the area of quality and safety, mealworm beetle larvae have been shown to have a promising nutritional profile that can be adapted to meet specific product requirements through targeted feeding and optimized harvesting times. Particularly noteworthy features are the high protein content and favorable fatty acid profile, both of which will be increasingly sought after by consumers in the future as they focus more on health and fitness-oriented nutrition. Product safety can be ensured through controlled rearing conditions and standardized processing procedures and should be verified and certified by independent institutions in order to build consumer confidence. However, further research is needed in some areas, for example to gain a better understanding of the role of chitin content and to fully assess the potential allergy risks. Optimizing manufacturing processes with regard to sensory and techno-functional properties also remains an important area for further development.

Analysis of the primary research data shows that there is significant potential for optimization in the transition from pilot facilities to industrial facilities. The largest levers that can be pulled to improve the environmental footprint are the selection of the feed and energy consumption. The use of by-products from the food industry as feed can significantly reduce environmental impact, although the physiological requirements of mealworm larvae must be taken into account. When considering the use of by-products as animal feed, it should be noted that EU feed regulations also apply to insect farming, meaning that many nutrient-rich by-products cannot be used as feed for insects. It is also necessary to examine the extent to which the use of by-products as feed for insects is beneficial from an environmental and economic perspective compared to alternative uses. The use of renewable energies and efficient production systems could further reduce the environmental footprint. Integrating mealworm farming into regional economic cycles and utilizing by-products from mealworm farming also offer promising approaches to sustainable production.

Consumer acceptance remains to be a key challenge, but positive developments are also evident: approximately 45% of consumers are generally willing to consume insect-based products. To expand this base and convert it into actual behavior, targeted product development and marketing strategies are required. Processed products that use insects as an "invisible" ingredient are much more widely accepted than whole insects. The snack sector in particular offers promising opportunities. Important success factors include clear yet subtle insect-labeling, communication that focuses on naturalness, and the provision of taste experiences through product tastings.

To secure the future role of insects in human nutrition, it will be crucial to holistically consider and deepen our understanding of these different aspects and how they interact with each other (◆ Figure 2). Insect-based products must meet consumer expectations and be competitively priced. At the same time, the optimization of production processes must take into account both quality and safety aspects, as well as sustainability goals. The choice of feed and rearing conditions plays a key role, as they directly influence both quality parameters and sustainability aspects, and have an indirect impact on consumer acceptance. Consequently, an integrated approach to the production and marketing of mealworm larvae can help realize the potential of insects as a sustainable and widely accepted protein source for the future food system.

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Disclosure on Conflicts of Interest and the use of AI
The authors declare that there is no conflict of interest and that no AI applications were used in the creation of the manuscript.

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