Environmental Engineering and Management Journal

October 2022, Vol. 21, No. 10, 1657-1671
http://www.eemj.icpm.tuiasi.ro/; http://www.eemj.eu
http://doi.org/10.30638/eemj.2022.148

"Gheorghe Asachi" Technical University of Iasi, Romania

Tenebrio molitor AS A NEW PROMISING ALTERNATIVE IN THE PRODUCTION OF FEED AND FOOD

Simona Errico*, Anna Spagnoletta, Stefania Moliterni, Salvatore Dimatteo, Alessandra Verardi, Paola Sangiorgio, Ferdinando Baldacchino, Roberto Balducchi

Laboratory of Bioproducts and Bioprocess, ENEA – Trisaia Research Centre, S.S. Jonica 106, km 419+500, I-75026 Rotondella (MT) - Italy

Abstract

The global population is growing and the ever-increasing need for proteins from sustainable sources requires urgent actions. The insects represent an alternative solution for several reasons: their nutritional profile is comparable to that of meat from other meat livestock; they can be easily and sustainably reared due to high fertility and reproductive rate; insect rearing facilities can be realized everywhere worldwide; reared insects' availability is not subjected to seasonality; they can grow on low-value substrates such as agri-food by-products. Among these good-to-eat insects, *Tenebrio molitor* (TM) is gaining rising attention from academia and the business world, also in the light of the recent favourable opinion of EFSA and the even more recent approval by the European Commission for the use of mealworms as a Novel Food.

Despite the enormous potential of TM, some aspects related to the impacts on human health have yet to be analysed and some regulatory, psychological and cultural barriers have yet to be overcome in the Western countries. On the other hand, the feed production from TM larvae will be more significantly promoted, since TM feed, already used in Europe for pets and aquaculture, has been approved for monogastric terrestrial animals and poultry at the end of 2021.

Key words: alternative protein sources, circular bioeconomy, edible insects, food safety, *Tenebrio molitor* rearing

Received: April, 2022; Revised final: October, 2022; Accepted: October, 2022; Published in final edited form: October, 2022

1. Introduction

The demand for more food connected to the increase in the planet population places the world of research in front of a fatal challenge. Indeed, it is necessary to limit the negative impacts on the environment and climate generated by the conventional food production system and, at the same time, ensure an increase in the availability of healthy and nutritionally balanced foods. Therefore, it is necessary to stop the present unsustainable productions and frame the new sources of nutrients, especially proteins, in a sustainable circular economy perspective. The new strategies implemented to meet this challenge consider the use of insects as one of the most promising opportunities due to their peculiar characteristics that make them suitable for the role of alternative sources of proteins and other valuable substances (Ordoñez-Araque and Egas-Montenegro, 2021). In this context, *Tenebrio molitor* (TM) can represent a very interesting and promising alternative.

From this point of view, 2021 can be considered the year of TM, a beetle of the Tenebrionidae family. It was the first insect approved by the European Commission (EC) for human consumption, in June 2021, after receiving the favourable opinion of EFSA in January of the same year (EC, 2021a; EFSA NDA, 2021). Europe's interest in insects as alternative sources of protein is demonstrated by the subsequent approval of the

* Author to whom all correspondence should be addressed: E-mail: simona.errico@enea.it ; Phone: +39 0835974474

Locusta migratoria in November 2021 (EC, 2021b) and of *Acheta domesticus*, in February 2022 (EC, 2022). At this moment, TM is the only insect approved by EC for using larvae (also known as "mealworm") in human nutrition, while the other two insects are approved for using adults.

Authorization as Novel Food involves compliance with certain regulatory restrictions in Europe. A proposer who wants to produce and market a new product in Europe must apply to the EC, which takes advice from certain relevant bodies (EFSA - European Food Safety Authority, is involved in food). After the favourable opinion of the relevant body, the EC can approve or reject the application.

The approval is valid only for that specific product and all the conditions detailed in the dossier. Anyone wishing to produce the same food can either become a partner or contractor of the proposer or submit a certification to the EC, which guarantees compliance with all the approved conditions and parameters.

For whatever changes, even minimal, they must submit a new application to the EC, as if they wanted to produce and market a completely different product and wait for EC approval. All this ferment, especially in EC, is due to the need to find valid alternative sources of protein, given the growing demand and the exponential increase in the world population (Derler et al., 2021). There are relevant innovations on TM use also in the production of feed. Already used for pets feed and aquaculture since 2015, it was approved in August 2021 as feed for poultry and monogastric terrestrial animals (EC, 2021c). In this review, we summarize the state-of-the-art on TM larvae (TML) products and on their possible uses. Furthermore, we make an analysis of the challenges to face for the full use in Western countries of this interesting matrix.

In fact, while the scientific and the business communities are increasingly interested in this insect both as an alternative source of good quality protein and in the use of many of its derivatives, there are still many challenges to be faced. Obviously, the massive use of TM and its products requires a large-scale TML rearing. At the moment, neither of these activities is sustainable, neither environmentally nor economically, unless specific measures are taken, which we will discuss in more detail in the dedicated paragraph.

One proof of this is that despite the many beneficial effects of TML derivatives, there is currently no product or drug based on TML derived peptides on the market, probably because it is still too expensive to produce them. Another crucial aspect is related to health and food safety. If rearing and production are not conducted under certain conditions, the risk of contamination is very high. Last but not least, cultural and legislative barriers still need to be overcome, the latter only in part recently contained.

2. TM products: sectors of use and biological effects

2.1. Nutritional aspects of Tenebrio molitor

Because TM has an excellent nutritional profile and very attractive characteristics, it has recently been greatly re-evaluated. Its products are an excellent alternative to meat and valuable for many other uses (Errico et al., 2022). In fact, TML are rich in protein, fat and micronutrients, which include sources of copper, iron, zinc, magnesium, potassium and phosphorus (Ghosh et al., 2017; Wu et al., 2020); mealworms are also rich in vitamins such as E, B12, B3, B2, B5 and H (Costa Rocha et al., 2021; Moruzzo et al., 2021b). In addition, two valuable antioxidants are in TM oil: tocopherol (Vitamin E) and polyphenols (Son et al., 2020). According to Ghosh et al. (2017), TML's iron and zinc contents are found to be higher than those found in other animals, such as chicken, pork, and beef (Costa Rocha et al., 2021). TML have a nutritional profile with an average of 50% crude protein (on dry matter, DM) and 30% crude fat (Hong et al., 2020; Van Broekhoven et al., 2015). Nutritional profile's value changes depending on the rearing environment, the life stage and the substrate used to feed larvae, where the value of fat varies above all (Mancini et al., 2019a; Van Broekhoven et al., 2015). The lipid content is very rich in monounsaturated fatty acids (MUFA), such as palmitoleic (C16:1) and oleic (C18:1) acids, saturated (SFA) and polyunsaturated (PUFA) fatty acids, such as linoleic acid (C18:2). TML also meet the demand for essential amino acids (EAA) as they are rich in leucine, isoleucine, lysine, tyrosine, valine and methionine (Gkinali et al., 2022).

2.2. Sectors of use and biological effects

TML products are oil, flour, protein, peptides, chitin, chitosan and frass: this review will deal mainly with the use of proteins, peptides, oil, and flour. According to Regulation (EU) 1017/2017, TML can be used dried or frozen for livestock or live (in a few EU member states). They can be used as flours and oils and partially replace some conventional ingredients, such as soybean-fish-wheat meal/oil. Several authors have evaluated animals' growth and health performance after the inclusion of TML meal and oil in feed, and the results have been satisfactory. In aquaculture, for example, TML-based feeds have been evaluated positively for rainbow trout, tench-bream and European sea bass (Moruzzo et al., 2021b).

In addition, TM meal and oil have been used as an alternative to soybean meal and oil in the feeding of broilers (Sedgh-Gooya et al., 2021), free-range soy and rabbits (Gasco et al., 2019) with good results. TM oil can be used as a substitute for palm oil in multiple products, poultry feed, and many other health applications due to its anti-inflammatory properties and Omega 3 content (Errico et al., 2022). Benzertiha et al. (2019) evaluated the effects of replacing palm oil and poultry fat with TM oil. These authors note a significant reduction in liver size, triglyceride and total cholesterol concentration, and an increase in n-3 and n-6 fatty acids in the breast muscle tissue of chickens that can be attributed to the high PUFA content in TM oil. TM fat may also be an excellent alternative to soy fat in rabbit diets. Indeed, Dabbou et al. (2020) saw a change in FA profile in diets with the highest MUFA value by supplementing the feed with TM fat. This supplementation proved to be very useful in increasing animal welfare, probably because insect fat plays an important role in containing pathogen growth (Errico et al., 2022), although further studies are needed on the impact of TML meals on microbial activity and gut microbiota of rabbits (Dabbou et al., 2020).

Other possible applications of TML meal are in the industrial sector and as food (supplement in food, snacks, bakery products, meat products). The proteins obtained can be used in food because they contain all the EAA (Costa Rocha et al., 2021). Thanks to their high nutritional value and sustainable production, insects could be an excellent alternative for human nutrition, partly satisfying the growing demand for food (Van Huis et al., 2017). Degreased worm powder can be used as a functional ingredient in food due to its high antioxidant capacity (Moruzzo et al., 2021b). One of the applications of TM flour is in bakery products, replacing wheat flour with percentages between 5 and 10%. The doughs and bread obtained in this way show more digestibility and better nutritional characteristics. They gave good results also in terms of volume, softness and colour (Gkinali et al., 2022). In addition, TML in the form of whole or pre-treated flour can be used for the preparation of meat products, such as sausage emulsions, by replacing 10% pork with untreated, defatted or acidified TM flour (Kim et al., 2016). According to Son et al. (2020), TM oil is very similar to vegetable oil and usable in nutrition, as it is rich in bioactive nutrients, such as ɣ-tocopherol, an antioxidant, and polyphenols, while the cholesterol content is shallow.

The scientific world is particularly interested in TM proteins and peptides, besides food and feed, because of their further considerable applications in pharmaceuticals and their nutritional and health effects. Some of the possible applications of proteins and peptides are mainly in the medical field for their anti-diabetic, anti-ACE, anti-microbial, anti-thrombotic, antioxidant and anti-inflammatory, anti-freeze and hepatoprotective properties (Errico et al., 2022). In their study, Seo et al. (2017) investigated the effects of TML extracts on the possible reduction of adipogenesis and obesity for their possible use as replacement of currently used drugs which are effective but have many side effects. The tests were conducted in vivo on mice fed different percentages of TML. They demonstrated the anti-obesity capacity of TML extracts by assessing parameters such as in vitro cytotoxicity, intracellular lipid accumulation, intracellular triglyceride content, gene expression and protein production. TM oil is rich in MUFA and PUFA and has excellent anti-inflammatory properties. It has a significant impact on cardiovascular disease, may also promote brain development of children during pregnancy and have beneficial effects on lactation (Errico et al., 2022). Lee et al. (2021) studied the effect of TM meal supplementation on hind limb atrophy in rats, particularly on the soleus muscle. They saw a stimulation of muscle protein synthesis and an inhibition of muscle protein degradation after 5 weeks of dietary supplementation, a promising result in combating sarcopenia.

2.3. TM Bioactive compounds and biorefinery model

Insect products have been shown to have remarkable biological properties due to some special molecules: bioactive compounds. These can interact with components of living tissue to produce a positive effect on human health. Insect-based bioactive compounds include mainly peptides and lipids, and TM products are an interesting natural source of them (Fig.1).

In addition, some TM peptides have antioxidant and anti-inflammatory activity against hypertension and diabetes. Moreover, some authors, such as Navarro del Hierro et al. (2020) demonstrated the inhibitory effect on pancreatic lipase using bioactive extracts of mealworm obtained by pressurized liquid extraction using aqueous ethanol as solvent. In similar research, Wu et al. (2020) obtained natural anticancer chemotherapeutic agents from the lipid fraction of TM. Table 1 shows some studies about possible positive effects of TML extracts and oil on human health. Costa Rocha et al. (2021) introduces the concept of biorefinery applied to edible insects and specifically to TM. Similarly to a refinery, in fact, from TM is possible to extract high added-value molecules using green technologies, such as non-conventional eco-friendly extraction methods (Costa Rocha et al., 2021).

The application of this concept can generate environmentally sustainable products, with high economic value, through innovative technologies, starting from the collection of organic waste and arriving at the final consumption, in a circular economy perspective. Various products can be obtained from oil and extracted protein by applying the biorefinery concept. For example, it can produce biodiesel from oil extracted with supercritical fluid extraction (SFE-CO_2) (Fig. 2). Additionally, thanks to bioactive compounds, other extraction products can be used as food and feed components; for example, the protein fraction obtained by the same process can be used in animal feed. TM fat for biodiesel production could be an alternative and sustainable resource that could decrease the cost of this product (Moruzzo et al., 2021b). The concept of biorefinery related to the recovery of high value-added products in insects is still in the embryo and needs more attention, as well as deeper studies.

Fig. 1. Properties of bioactive peptides from *Tenebrio molitor* larvae (in vitro studies) (adapted from Errico et al., 2022)

Table 1. Possible positive effects of *Tenebrio molitor* larvae extracts and oil on human health

Possible positive effects	***Bibliographic reference***
Protection against hepatocellular carcinoma	Zepeda-Bastida et al., 2021
Inhibition of BACE-1 enzyme activity related to accumulation of β-amyloid	Youn et al., 2014
Cardiovascular protection, promotion of fetal brain development, positive effects on breastfeeding	Koletzko et al., 2008
Obesity-alleviation (in vitro and in vivo)	Seo et al., 2017
Anti-thrombosis, antioxidant and hemolytic activities against human red blood cells	Pyo et al., 2020
Promotion of platelet aggregation	Pyo et al., 2020
Antioxidant capacity and anti-inflammation activity	Son et al., 2020
Antioxidant and tyrosinase inhibitions activities, perhaps also skin-whitening effects	Kim et al., 2018
Prevention of muscular atrophy	Lee et al., 2021
Prevention of lipid oxidation in free radicals and hydroperoxides in foods	Son et al, 2020

3. Challenges in Western countries

3.1. Sustainability of TM rearing

According to several authors, the production of farmed insects is more sustainable than livestock raised industrially to produce meat (Oonincx and de Boer, 2012). Rearing insects is considered sustainable also due to their higher Feed Conversion Ratio (FCR) and edible portion than other farmed animals (van Huis et al., 2013).

Land used to produce 1 kg of edible protein with TM is 10% of that needed for beef (Baiano, 2020; Flachowsky et al., 2017). Oonincx and de Boer (2012) estimated the land use for 1 kg of fresh TM larvae based on economic allocation. This value is split between 3.03 m^2 for mixed grains, 0.51 m^2 for carrots and only 0.01 m^2 for TM farm.

The consumption of water for livestock farming is under the attention of FAO (Baiano, 2020), as it is an important parameter to assess the breading sustainability. TML can absorb water through the cuticle in environments with high humidity (Punzo and Rosen, 1984): breeders exploit this characteristic to feed TML plant sources of water, in addition to the dry diet, instead of water as such. The decision to provide a plant supplement to the diet is justified because the increasedavailability of free water increases growth and reduces development times (Liu et al., 2020; Özsoy, 2019).

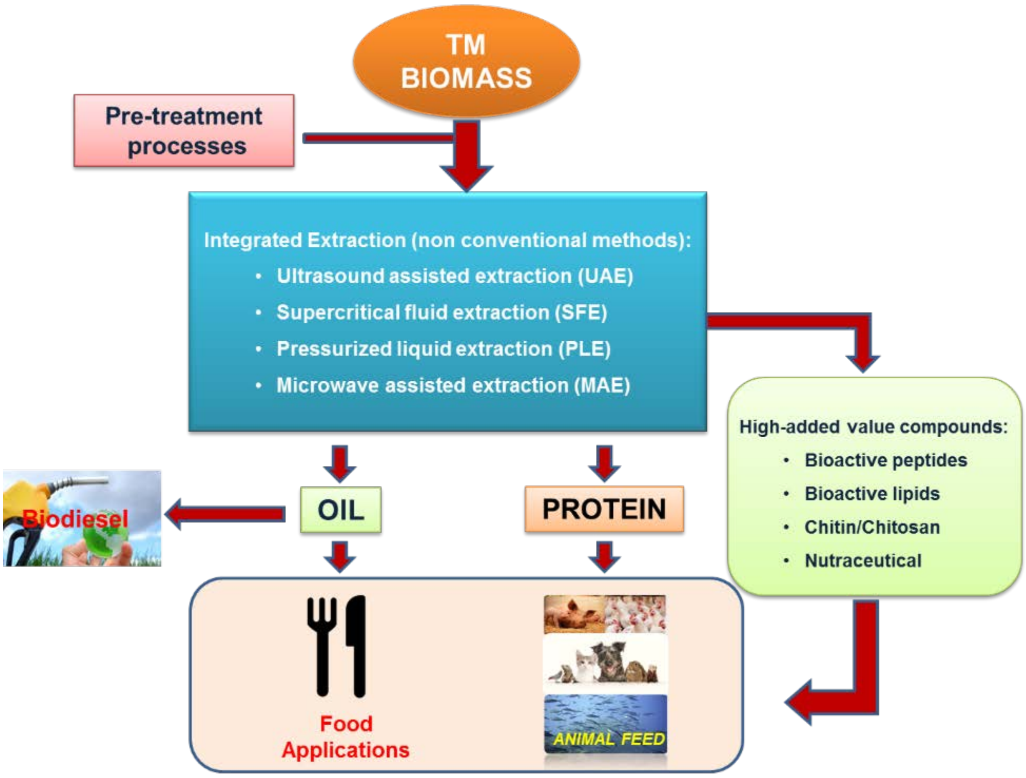

Fig. 2. Flowchart of biorefinery concept applied for *Tenebrio molitor* (adapted from Costa Rocha et al., 2021).

In farming, mealworm grows using carrots as a water source (Dreyer, 2021), but other vegetables such as potatoes and cabbages are also used (Liu et al., 2020; Rumbos et al., 2021). The water footprint was estimated at 112 L/g protein for beef and only 23 L/g protein for mealworms, mainly included in the feed production phase (Miglietta et al., 2015). Thus, the water footprint strongly depends on the diet type fed to the insects. Dreyer et al. (2021) performed an LCA on a small-scaled TML production located in an Austrian mountainous area about 1,000 m above sea level. According to their studies, heating-related energy consumption is highly relevant for the mealworm production site in a cold Country. Additionally, the heating demands increase more in winter due to a potential decrease in outdoor temperatures. On-farm energy demand related to the use of electric appliances (heaters, humidifiers, wacker plates, vacuum cleaners) and feed processing equipment (mill and mixing machine) represents a hot spot (Dreyer et al., 2021).

Due to mealworms poikilothermic nature, they do not use the energy in feed to maintain a constant body temperature, but instead to grow (Nakagaki and Defoliart, 1991). Although poikilothermy decreases feed consumption, insects' body temperatures are affected by ambient temperature. Thus, local climatic conditions directly influence the energy consumption of mealworm rearing. In contrast, cooling-related energy consumption could be relevant in a hot country, particularly in the summer season.

Therefore, energy demands are strictly dependent on the country's latitude and climate.

Nonetheless, insect farming will be more sustainable using substrates without competing with feeds for other farmed animals (Pinotti and Ottoboni, 2021). Insect farms generally use commercial substrate (Oonincx et al., 2015), mixed grains (Oonincx and de Boer, 2012), chicken feed (Bordiean et al., 2020; Harsányi et al., 2020) and wheat bran mixed with corn seeds (Dreyer et al., 2021). Sustainability would increase with higher use of wheat bran (a by-product of the transformation of wheat) and less consumption of seeds for human and animal nutrition. Among other things, wheat bran appears to be more suitable than chicken feed in the TM reproduction phase (Naser El Deen et al., 2021).

A considerable increase in the environmental and economic sustainability of the TM rearing can result from the use of agro-industrial by-products as feed (Pinotti and Ottoboni, 2021; Derler et al., 2021). Bioconversion of wet by-products and waste through insects is more feasible with *Hermetia illucens* L., while expired bakery products could be better bio converted by mealworms (Ites et al., 2020). Suitable moist by-products such as brewery by-products require dehydration to prepare TM feed, thus negatively affecting energy consumption (Dreyer et al., 2021). Brewer's spent grain has been tested alone or in combination with other by-products (van Broekhoven et al., 2015). Compared to residual cookies, it induced significantly faster larval growth, higher larval protein content and lower fat content (Mancini et al., 2019a). Brewer's yeast as a wheat bran supplement (at doses of 30% and 50%) significantly improved the weight gain, specific growth rate and reduced larval period (Kim et al., 2019). Among the most widespread agro-industrial by-products, inclusion of olive pomace up to 25% in wheat middlings diet represents the best compromise between larval growth performance and their nutritional properties (Ruschioni et al., 2020). Rovai et al. (2021) tested carrot pomace and proposed an optimized diet with dry carrot pomace (36%) balanced with wheat bran.

Among the cultivation residues, spent mushroom substrates can be advantageously mixed in standard diets for TML. Diets supplemented with <40% of spent *Lentinula edodes* (Berk.) substrate produce performance (larval weight and larval survival) like that of conventional diet (Li et al., 2020). The fungus species influences the larval performance which is better for *Flammulina velutipes* (Curtis) than for *Pleurotus eryngii* (DC.) substrates (Kim et al., 2014). Crop residues rich in lignocellulose were also tested. Rice bran, rice straw and corn straw have supported larval growth, but their low protein content limits their use in diets. However, the results show that mealworms can partially degrade cellulose, hemicellulose and lignin (Yang et al., 2019). Often the use of by-products in diets must include multiple substances for the optimal feed. A methodological approach based on self-selection by TM was used by Morales-Ramos et al. (2020) to select the best diet composition.

In a circular economy framework, it is also fundamental to evaluate the use of by-products from an economic point of view. Rumbos et al. (2021) reared TML on different seed cleaning process by-products, combining FCR and Specific Growth Rate (SGR) to Economic Conversion Ratio (ECR). This method showed that the wheat bran and yeast control diet (9:1) had 2-3 times higher ECR values than lupine, triticale, barley and oat by-products. This result suggests that each feed must be evaluated based on economic efficiency, although the cost of other local factors such as energy and labour must also be considered.

Integrating TM rearing into a broader circular economy context could help reduce costs and increase sustainability. Valorizing the residues of TM rearing is one way of closing the cycle. As shown in Fig. 3, insect waste streams prove to be promoters of crop and soil health (Torgerson et al., 2021). Used as fertilizers and bio stimulants, they can re-enter the primary crop production, which, in turn, generates waste usable for feed for mealworms. Exploiting all the products that may derive from rearing waste can give more value to the entire chain. Exuviae and dead insects (larvae or adults) are excellent sources of chitin and chitosan. These macromolecules have numerous applications in various sectors such as chemicals, food, pharmaceuticals, textiles and cosmetics (Errico et al., 2022). All this confirms the potential and multifunctionality of all products derived from TM, including waste products.

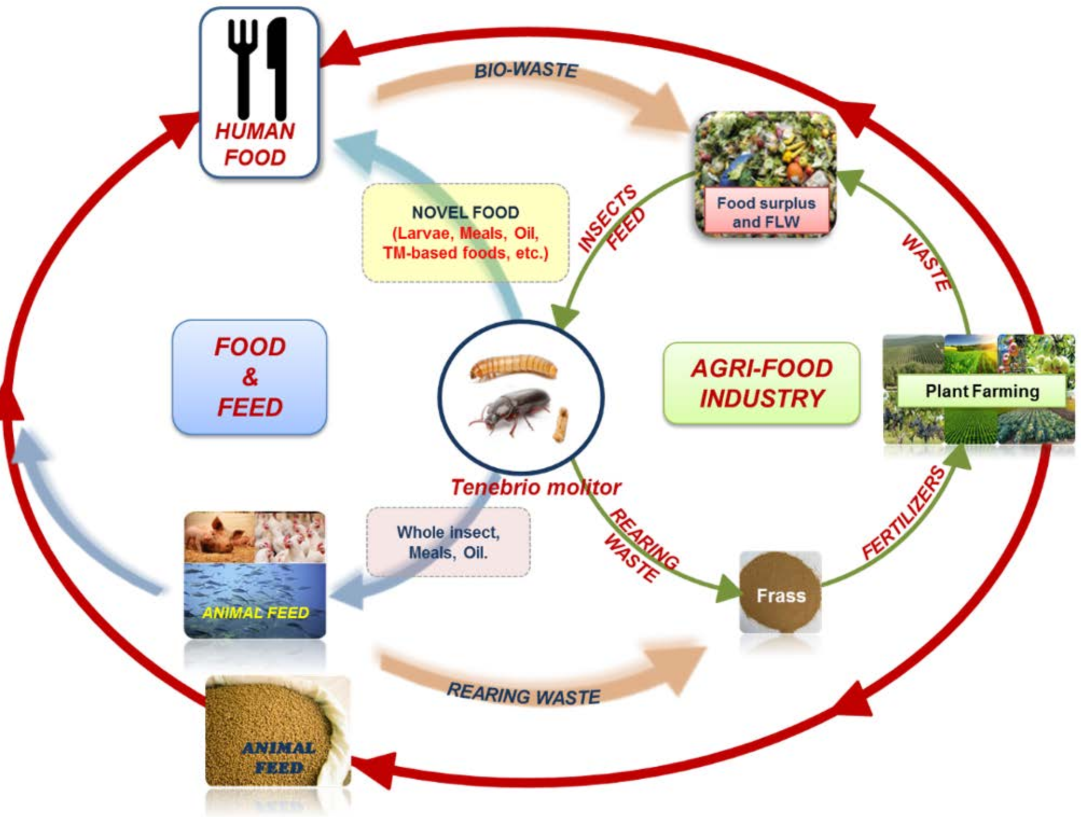

Fig. 3. *Tenebrio molitor* in the Circular Bioeconomy

3.2. Safety

Whole edible insects and their insect-based foods, given their high nutritional profile and a high degree of sustainability, represent an excellent source of bio-compounds and protein. These can be used as valuable substitutes or supplements to traditional protein sources even if their food safety is one of the main obstacles to the acceptability of insects as food and feed, especially in Western countries (Imathiu, 2020).

Edible insects, in addition to hidden exogenous (farming conditions, harvesting and processing, etc.) and endogenous (insect itself or its food, etc.) risks to human and animal health (EFSA, 2015; EFSA NDA, 2021), are responsible for potential food safety hazards. The main hazards associated with them can be grouped into microbial, chemical, toxic, allergenic and zoonotic hazards (Rumpold and Schlüter, 2013a, b), as shown in Fig. 4.

3.2.1. Microbial risks

Consumption of fresh larvae is often associated with contagions from foodborne pathogens, whereas consumption of insect-based foods is often related to contagions from sporulated pathogens resistant to industrial food treatments and can grow during the storage period (Messina et al., 2019; Vandeweyer, 2020).

Observing the data shown by Garofalo et al. (2019), the main microbial risks of fresh and processed edible insects are represented by: high total count of aerobic bacteria, some also responsible for food alteration (*Bacillaceae*, *Enterobacteriaceae*, *Enterococcaceae*, *Staphylococcaceae*), presence of sporogenous bacteria potentially sensitive to heat treatments, yeasts and moulds.

Taking all those measures leading to the inactivation of the gut microbiota of the insect can minimize most microbial risks. To this end, according to some authors, various treatments may be effective: fasting, in particular, performed before any transformation treatment (Garofalo et al., 2019); the using sterilized feed during rearing (Chung et al., 2013); the various pre- and post-processing heat treatments (Bellucco et al., 2013; Vandeweyer et al., 2020), in particular, those that ensure the survival of the bacteria responsible for beneficial effects (Grau et al., 2017). Microbial surveillance, also extended to feed used in insect farms, can reduce their transmission and this was verified for *Salmonella* sp against TML (Wynants et al., 2019). When agro-industrial by-products serve as feed, it is critical to apply strict microbial surveillance in the production and storage of these substrates, thus blocking the introduction and spread of these contaminants within the supply chain (FAO, 2021). Currently, insects and their derived foods are of low dietary risk only towards determinate food pathogens such as hepatitis A virus, hepatitis E virus and group II norovirus. However, the same authors recommend extending the research to other species using more innovative methods (Vandeweyer et al., 2020).

3.2.2. Chemical and toxic hazards

As observed by Houbraken et al. (2016) and Imathiu (2020), insects can present several chemical and toxic risks, including:

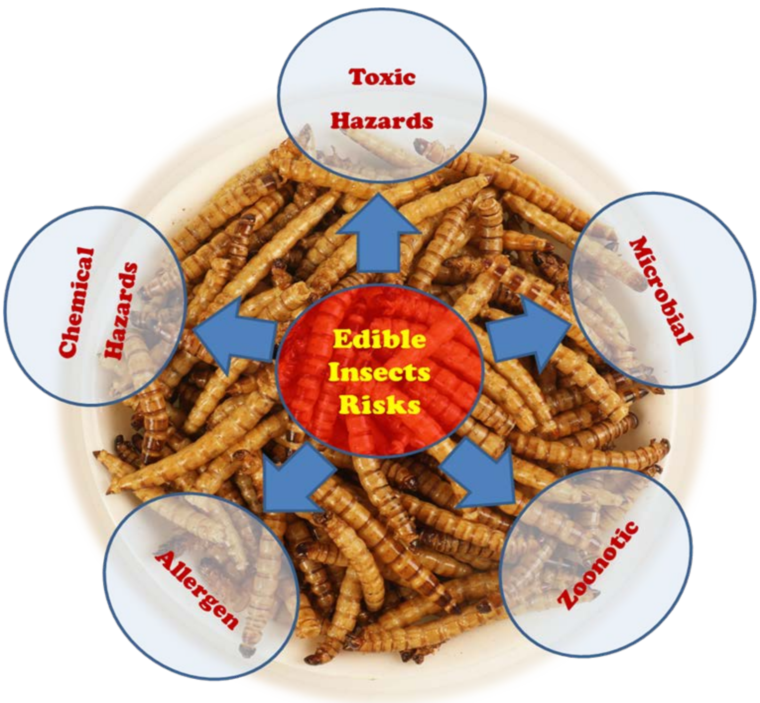

Fig. 4. Safety risks of edible insects

- antinutrients (tannin, oxalate, cyanide, phytate, saponins, alkaloids, and heat-resistant thiaminases),
- species-specific synthesized toxins, produced in response to hazards or sequestered directly from the plants they feed on,
- heavy metals (selenium, cadmium, lead, mercury, and arsenic) and other harmful chemicals such as pesticides accumulated using contaminated feed.

There is no evidence of mycotoxin accumulation (van der Fels- Klerx et al., 2018). Antinutrients in edible insects are not toxic but reduce the absorption of essential nutrients in the body, thus decreasing the nutritional value of the food (Ekpo, 2010; Iduwu et al., 2020). In contrast, heavy metals can be of concern, as some authors have found a tendency for TML to accumulate selenium and cadmium beyond acceptable levels for food consumption (van der Fels-Klerx et al., 2018; van der Spiegel et al., 2013). Kooh et al. (2020) have recently introduced a downstream HACCP protocol for the entire insect supply chain, from rearing to consumption, to reduce biological and chemical contamination and assess the risks associated with the different manufacturing processes of TML powders intended to produce various foods.

3.2.3. Allergen risks

This topic involves both consumers of insects (Ribeiro et al., 2017) and employees of insect rearing facilities exposed to inhalation or contact with materials contaminated with possible insect allergens (Grau et al., 2017). As arthropods, insects contain allergens like tropomyosin (Ayuso et al., 2002), arginine kinase (Binder et al., 2001), and glutathione S-transferase (Galindo et al., 2001).

These allergens are responsible for cross-reactivity to insects for consumers allergic to house dust mites or crustaceans (Broekman et al., 2016; Verhoeckx et al., 2014). In addition, chitin allergenicity has only been confirmed by inhalation and is not related to direct consumption (van der Fels-Kelerx et al., 2018). Various authors have investigated the possible effect of insect processing methods in reducing allergenicity. It appears that heat treatments such as blanching, boiling, frying or baking affect the solubility of TM meal allergens, but their degree of allergenicity remains unaffected (Broekman et al., 2016; van der Fels-Kelerx et al., 2018). Since the presence of gluten on the surface of TML and in their intestines could limit their inclusion in products labelled "gluten-free," a great deal of attention is being paid to the relationship between TML and celiac disease. Data from Mancini et al. (2020) showed that washing and fasting could effectively reduce the levels of gluten carried by TM to below 20 ppm. Introducing clear information and warnings on insect-containing food packages is fundamental and highly recommended to mitigate or eliminate allergenicity risks (van Huis et al., 2021).

3.2.4. Zoonotic risk

Given the current historical moment marked by the SARS-CoV-2 pandemic we are experiencing, the zoonotic risk is now more in the consumer spotlight. Though studies show that insects and feed do not contribute to the transmission of SARS-CoV-2 and other coronaviruses (Dicke et al., 2020), Khalil et al. (2021) showed a significant decrease in willingness to consume insect-based foods after the COVID-19 outbreak.

Some authors argue that, unlike livestock, insects do not pose a high zoonotic risk due to their evolutionary distance from mammals (Dicke et al., 2020). They cannot accumulate mycotoxins (Niermans et al., 2019; van Broekhoven et al., 2017), pathogenic viruses, and prions, but can act only as "zoonotic vectors" (van der Fels- Klerx et al., 2018). So, when raised and processed in controlled environments, their food safety is high (Klunder et al., 2012; Rumpold and Schlüter, 2013a, b), and the risk of zoonosis is extremely low (EFSA, 2015). However, this does not mean that the risk can be eliminated. Recent studies have shown that prion diseases (transmissible spongiform encephalopathies) are lethal neurodegenerative diseases that affect humans and livestock (Grau et al., 2017). Furthermore, insects are a reservoir of a high diversity of RNA viruses, whose potential risk to human health is still unexplored (Käfer et al., 2019).

EFSA's recent statement regarding the safety of TM for the proposed levels and uses (cookies, pasta, snacks, bars) confirmed many scientific data found to date in safety terms (EFSA NDA, 2021).

3.3. Cultural barriers

Until last year alone, many studies reported that about 2 billion people (3000 ethnic groups), distributed in 113 countries around the world, included in their daily diet the approximately 2,000 species of edible insects usually collected in nature or reared (del Mastro, 2021; Deroy et al., 2015; Tao and Li, 2018; Thrastardottir et al., 2021; van Huis et al., 2021). A very recent study by van Huis et al. (2022) radically re-examines the economic, cultural and social profile of those defined as "insect-eaters". The author strongly questions the exact estimate of the total global population that consumes insects. It may only be a few "hundreds of millions" of people who "really" eat insects instead of the 2 billion (25% of the world population) as presented in the FAO/WUR report and by IPIFF (IPIFF, 2020; van Huis et al., 2013;). Therefore, the value used so far could only be considered an overestimate of the actual number of insect consumers (van Huis et al., 2022). The interest in insects, both as food and feed, has grown exponentially in the last 10 years (van Huis, 2021).

However, the process of economic and cultural globalization is generating negative repercussions towards the view of "insects as food". For example, in the Tropics, territories considered of choice for insect consumption, there has been a lower consumption of insects as food in recent years because of an increased rejection by the population. The causes of this phenomenon are the westernization of the eating habits and the depopulation of rural centres where the consumption of insects is more rooted and widespread (Hlongwane et al., 2020; Muller, 2019; Niassy et al. 2016). On the other hand, the Western people, despite the enormous attention devoted by the scientific community to "edible insects" (803 articles in the decade 2011-2020) (van Huis et al., 2021), still seems very reluctant to eat insects and manifests much difficulty in changing its eating habits (De Carvalho et al., 2020; Hartman et al., 2015).

Therefore, this reluctance to eat insect-based foods is no longer a Western prerogative but a "universal" one. So, it is urgent and of paramount importance to implement all strategies to foster change in the attitudes and behaviour of the entire world population towards edible insects (van Huis et al., 2021) if the goal is to introduce at least partial insect consumption into the human diets.

The big challenges in recent years have been to add more detail and better define the profile of the "insect eater of the future" and to study the key factors that most influence the perception and acceptability of especially Western consumers towards insect foods (Hartmann and Bearth, 2019; Kauppi et al., 2019; Rumpold and Langen, 2019; Wendin and Nyberg, 2021). The result that emerges from these studies is a rather complex picture, composed of very different but at the same time firmly correlated factors that may vary throughout an individual's lifetime (Moruzzo et al., 2021a; Ngo and Moritaka, 2021). The main barriers to Western consumer acceptance of insect food products appear primarily psychological, cultural, and age-related (House, 2019).

In most Western populations, the mere thought of consuming insects as food essentially generates behaviours of pure "food neophobia" and "deep disgust". Insects are not "familiar to them as food" (Sidali et al., 2019) and are associated with "negative personal experiences" (Moruzzo et al., 2021a). They are especially linked in a "generalised" way too contaminated, dirty, unhygienic environments, deteriorating organic matter, and represent a public health hazard (De Foliart, 1999; Deroy et al., 2015; Looy and Wood, 2006; Shelomi, 2015). These sometimes illogical and inconsistent behavioural responses to insects as food are dictated, according to Deroy et al. (2015), by so-called "environmental confound", the consideration of insects as a "one-size-fits-all" category, and, most importantly, a lack of awareness and knowledge of the existence of "insect varieties" (e.g., edible and inedible) (Looy et al., 2014; Shelomi, 2015).

Older people tend to be more neophobic than younger people (Jaeger et al., 2021). Children and adolescents - the segment that should be strongly targeted - show a more possibilistic approach and greater willingness about insects' consumption (Geertsen, 2019; Nyberg et al., 2021; Scaglioni et al., 2018).

Western consumers are not used to eating insects, so it is important to find strategies to explain their hygienic safety, environmental sustainability and goodness for health (van Huis, 2021). An effective way to make insects such as TM less unfamiliar and repulsive is to increase their degree of familiarity by including them in known food products (meat products, bakery goods, snacks, milk, etc.), thus making them "invisible" (Azzollini et al., 2018; Çabuk and Yilmaz, 2020; Cho et al 2018; Choi et al.,2017; González et al., 2019; Petrescu-Mag et al., 2022 Tello et al., 2021; Zielińska and Pankiewicz, 2020) and pleasant taste (Çabuk, 2021; Cicatiello et al., 2020, Wendin et al., 2021; Żołnierczyk et al., 2021).

Many studies have shown how exposure to insect-based foods, through sensory evaluation tests, and its frequency decrease the disgust factor among participants and increase their willingness to try to eat them (Barton et al., 2020; Mancini et al., 2019b; Woolf et al., 2019). The participant's education level and gender, together with the context (location, type of participants, the notoriety of the organizers, etc.) in which insect foods are offered, affect both the number of attendees and the degree of acceptance. Males of young age and higher education are the most willing to eat insect-based foods (Arena et al., 2020; Videbæk et al., 2020). All contexts characterized by positive emotions shared with friends (such as in pubs, food festivals, etc.), new trends launched by well-known chefs (Dion-Poulin et al., 2021) or famous television programs, manage to address consumer choices differently (Arena et al., 2021; Motoki et al., 2020).

Schools could play a key role in increasing their awareness and moving toward including insects and their products in their diets (Jones, 2020; Nyberg et al., 2021). Consumers need increasingly qualified information about several aspects of insect consumption, including food safety, possible health benefits, sustainability, and environmental protection (Legendre et al., 2019; Mancini et al., 2019b; Palmieri et al., 2019).

Young consumers, as they become more aware and attentive to topics such as sustainability, environment and health, are more likely to change their diets towards more sustainable food choices (Guiné et al., 2021; Henault-Ethier et al., 2020; Saric et al., 2020; Sogari et al., 2020). Conversely, in adult consumers, environmental consciousness does not necessarily translate into a greater likelihood of consuming insects (Chang et al., 2019; Hartman and Siegrist, 2017; Lammers et al., 2019).

In contrast to the reluctance of the population to embrace this change in their diets, the scientific community has lately paid great attention to this issue, so much so that it is present in both the goals proposed by the "Agenda for Sustainable Development 2030" and in some strategies of the European Green Deal, such as Farm-to-Fork (EC 2019; 2020). Moreover, there is now a large amount of scientific information available on insect-based foods as a sustainable alternative to traditional protein sources (Gkinali et al., 2022; Sangiorgio et al., 2021).

Insect-enriched foods and beverages have begun to appear on the European market since 2014 but since 2018 there has been an acceleration leading to 82 insect-based products on the market in 2021. They include products like pasta, bread, crackers and energy bars (Khalil et al., 2021). Interventions to improve their commercialization can increase the recruitment of new consumers. These include the reduction of supply and storage distances, the presence in local supermarkets and not just online sales (Florença et al., 2021), appropriate marketing campaigns, such as their name, image, and price reduction (Hwang and Choe, 2020; Van Thielen et al., 2019).

These sectors, especially in Europe, are currently heavily penalised because they are limited by the European regulations still in force on edible insects and their products (Guiné et al., 2022). In other parts of the world, however, insects are increasingly being marketed as a protein and sustainable alternative for humans and as feed for livestock and aquaculture (Glaros et al., 2021).

4. Conclusions

Last year, 2021, saw the approval by the European Commission of the use of TM (for the first time in Europe) as Novel Food, opening new strong growth perspectives for its direct production and for its various derivatives. On the other hand, the approval of TM as a Novel Food subjects this insect to restrictive regulations that should be evaluated in further analysis, as they could inhibit a wider use of insects in human nutrition and better sustainability.

In addition to improving the sustainability of TM farms, scientific research will have to address concerns about food safety and possible effects on consumer health, as well as the elimination of cultural and psychological barriers that substantially inhibit the correct exploitation of TM. The scientific community has long proposed TM as an alternative protein source, although some regulatory obstacles have only recently been overcome. There are certainly many cultural barriers to get over, especially in the Western countries. However, it would seem that Europeans disgusted by foods containing insects are less and less, enticed by the nutritional characteristics, but only if the insects are no longer distinguishable on the dish and their presence is clearly marked among the ingredients or on the package. With the recent approval from the EC of TM for human consumption, the producers' market is also making substantial investments in this nutritional alternative source.

Tenebrio molitor is undoubtedly a very interesting insect that could have a central and innovative role in the nutrition of many Europeans in the not-too-distant future. This, however, provided that some critical issues are overcome, and that studies and investments continue to make its rearing fully sustainable.

Finally, it is essential to enhance and make effective communication that disseminates knowledge on the nutritionally beneficial effects and environmental benefits that can be obtained from the insects' farming in a context of circular bioeconomy. Only good information can change consumers' position for this new food source and modify their behaviours in favour of its regular consumption.

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