BRILL
WAGENINGEN
ACADEMIC

JOURNAL OF INSECTS AS FOOD AND FEED (2026) DOI:10.1163/23524588-BJA10398

Journal of Insects as Food and Feed
brill.com/jiff

RESEARCH ARTICLE

Solar drying of *Tenebrio molitor L*: Impact of covering materials on the physical and chemical properties of yellow mealworms

Alfredo Domínguez-Niño[1,2], *Paulina Guillén-Velázquez*[1,3], *Iris Santos-González*[4], *Mario Luna-Flores*[5] *and Octavio García-Valladares*[1*]

[1]Grupo de Secado Solar, Instituto de Energías Renovables-UNAM, Temixco, Morelos, México; [2]Dirección Adjunta de Desarrollo Científico, Secretaría de Ciencia, Humanidades, Tecnología e Innovación, México City, México; [3]Estancias Posdoctorales por México, Secretaría de Ciencia, Humanidades, Tecnología e Innovación, México City, México; [4]Investigadoras e Investigadores por México, Secretaría de Ciencia, Humanidades, Tecnología e Innovación, México City, México; [5]Departamento de Ingeniería de Procesos Bioalimentarios, Universidad Tecnológica del Centro de Veracruz, Cuitláhuac, México; *ogv@ier.unam.mx

Received 7 July 2025 | Accepted 10 March 2026 | Published online 30 March 2026

Abstract

The investigation evaluated the impact of different covering materials in solar dryers on the physical and chemical properties of yellow mealworms (*Tenebrio molitor* L.). Five solar dryers were constructed using different cover materials, including transparent polycarbonate, glass, acrylic, dark polycarbonate and aluminium coated with titanium oxide. Their performance was compared to an electric stove at 50 °C. The yellow mealworms dried in the glass cover dryer achieved the lowest moisture content (1.39%) in the shortest time (240 min), due to its high internal temperature (72.56 °C) and ability to transmit over 90% of solar irradiance. The drying process increased the concentration of nutrients, including total proteins content, fats, fibre, carbohydrates, and ash content, due to water removal. The total protein content increased significantly in all dried samples. However, changes in colour parameters were observed, with a decrease in lightness and variations in hue angle and chroma. The smallest total colour difference between fresh and dried samples (ΔE) was recorded using the electric stove (11.43), followed by the titanium oxide dryer (12.8). The study carried out suggest that the use of solar dryers with specific covering materials can preserve the nutritional and colour properties of yellow mealworms, with the titanium oxide dryer being a promising option due to its ability to retain heat and eliminated Ultra Violet radiation (UV) exposure. Also it was possible to conclude that edible insects, such as yellow mealworms, represent a promising alternative protein source to address global food security challenges due to their high nutritional value.

Keywords

drying technologies – novel food – nutritional properties – solar energy – ultraviolet radiation

1 Introduction

In recent years, the challenges associated with sustainable food production have intensified, particularly in developing countries. By 2050, global demand for animal products is projected to rise by 60-70% (Syahrulawal *et al.*, 2023), with dairy and meat consumption expected to increase by 74 and 58%, respectively,

Published with license by Koninklijke Brill BV | DOI: 10.1163/23524588-BJA10398

ISSN: 2352-4588 (online)

(Makkar, 2018). At present, meat remains the primary source of protein for a significant portion of the world's population; however, this growing demand for animal protein places considerable pressure on natural resources. Consequently, there is an urgent need to promote research into alternative protein sources that are sustainable, nutritious, and accessible in order to address future food security challenges (Muñoz-Seijas *et al.*, 2024). Edible insects represent a promising alternative to address current global food security challenges, as they combine high nutritional value – with proteins, fats, vitamins, minerals, and fibre – with environmentally sustainable production (Bogusz *et al.*, 2024; Lange and Nakamura, 2021). The nutritional quality of edible insects appears to be equivalent to, and in some cases even superior to, that of animal-based foods from birds and mammals (Lange and Nakamura, 2021). Worldwide, more than 2000 edible species have been identified (Jongema, 2017; Langston *et al.*, 2024), and Mexico stands out with over 540 recorded species, reflecting its high biodiversity and an ancient culinary tradition based on insect consumption (Ramos-Elorduy, 2008; Secretaría de Agricultura y Desarrollo Rural, 2018). Among the species with the greatest potential is the yellow mealworm (*Tenebrio molitor* L.), which offers advantages, including its high nutritional content and its ability to adapt to different substrates and rearing conditions (Langston *et al.*, 2024; Syahrulawal *et al.*, 2023). Yellow mealworm larvae are commercially used as animal feed and, in some regions – including parts of Africa, Asia, America, and Australia – for human consumption (Alves *et al.*, 2016; Kröncke *et al.*, 2018). More recently, the European Union approved their use as food (Turck *et al.*, 2023). *Tenebrio molitor* L. is an insect species that goes through four stages of development: egg, larva, pupa, and adult (Costa *et al.*, 2020). It feeds mainly on cereals, flour, and their derivatives. Its life cycle varies between 280 and 630 days, depending on environmental conditions (Azzollini *et al.*, 2016). Yellow mealworms are a promising source of essential minerals such as phosphorus and magnesium (Costa *et al.*, 2020). It should be noted that their iron and zinc contents are higher than those found in meats such as chicken, pork, and beef (Da Costa Rocha *et al.*, 2021). Fresh yellow mealworms contain between 59% and 68% moisture, with a water activity of approximately 0.96, making them highly susceptible to microbiological spoilage, lipid oxidation, and both enzymatic and non-enzymatic degradation reactions (Lenaerts *et al.*, 2018). Therefore, post-harvest drying is a fundamental step in ensuring the preservation and quality of products based on these insects (Kröncke *et al.*, 2019). Drying is one of the most widely used methods for preserving various agricultural and food products, including fruits (Sacilik and Elicin, 2006), vegetables (Miranda and Santos, 2020), processed foods (Castillo-Téllez *et al.*, 2019; Kumar *et al.*, 2016), edible flowers (García-Valladares *et al.*, 2023, 2024) and aromatic plants (Domínguez-Niño *et al.*, 2025). To increase consumer acceptance of insects, various processing technologies have been studied, mainly aimed at incorporating them in unrecognizable forms, such as powders (Liceaga, 2021; Melgar-Lalanne *et al.*, 2019). Freeze-drying is currently the most widely adopted industrial technique, as it effectively preserves key quality parameters, including colour, aroma, texture, nutritional value, and biological activity (Huang and Zhang, 2012). However, Kröncke *et al.*, 2018, in comparing drying processes, reported that freeze-dried larvae showed significantly higher oxidative status, while microwave drying and vacuum oven drying emerged as promising options (Kröncke *et al.*, 2018; Lenaerts *et al.*, 2018). Although these methods are often more economical than freeze-drying, they still involve relatively high energy consumption. To address these limitations, recent studies have investigated more sustainable and accessible drying alternatives.

Solar drying systems work by using solar radiation, making them a hygienic, safe, cost-effective, energy-efficient, and environmentally sustainable alternative for food preservation (Sharma *et al.*, 2009). In these systems, air flow is generated either by natural convection or by forced convection using devices such as fans. The drying process may involve the circulation of preheated air through the product inside a closed, shaded chamber, direct exposure to solar radiation, or a combination of both. They reduce the moisture content of food products through forced convection and natural ventilation, achieving levels that inhibit microbiological spoilage. This extends shelf life and allows for lower-cost storage and transportation. A critical factor in the efficiency of solar drying systems is the selection of construction materials, as these directly influence the absorption and transfer of solar energy to the product. The right choice of materials can improve the internal temperature of the dryer, thus improving dehydration performance (Mustapha *et al.*, 2026). In this study, five types of direct solar dryers with different types of covers were evaluated: transparent polycarbonate, glass, acrylic, dark polycarbonate, and aluminium coated with titanium oxide. The aim of this research was to assess the influence of these coating materials on the physical and chemical properties of yellow mealworms and

FIGURE 1 Different types of covers of solar dryers used in the drying process of *Tenebrio molitor L.* From left to right: polycarbonate, glass, acrylic, dark polycarbonate and aluminium with titanium oxide.

to compare the results with those obtained using conventional drying methods, such as an electric stove.

2 Materials and methods

Sample preparation

Tenebrio molitor L. was fed with wheat bran and probiotics; carrot was used as a water source. It was maintained at a temperature between 24 and 29 °C for 90 to 120 days until reaching the required average weight (approx. 15 mg). After that *Tenebrio molitor* L. reached the required weight, they were killed by blanching at temperatures above 90 °C for 3 min.

Drying

The drying process of yellow mealworms was carried out using solar dryers equipped with different cover materials, polycarbonate, glass, acrylic, dark polycarbonate and aluminium coated with titanium oxide, as well as a conventional electric stove set at 50 °C, on 26 February 2025 (Figure 1). The dryer has a drying area of 0.3 m^2, and its dimensions are 35 × 64 × 26 cm. The sample was spread on perforated polyethylene mesh placed on an aluminium grill through which air circulates, by natural convection, leaving the drying chamber from the upper side. Each dryer has distinct characteristics based on the type of material used in its construction. The dryer with transparent polycarbonate cover was made with protection from UV radiation, it is a material that can transmit over 86% of solar irradiance. The dryer with a glass cover is 6 mm thick and can transmit more than 90% of solar irradiance; an internal temperature of 72.56 °C was reached. The dryer with a transparent acrylic cover is a UV-resistant material, 5 mm thick, and can transmit more than 92% of solar irradiance; an internal temperature of 62.20 °C was reached. The dryer with a gray polycarbonate cover is a UV-resistant material, 6 mm thick, and can transmit 65% of solar irradiance; an internal temperature of 59.29 °C was reached. Finally, titanium oxide coating applied to an aluminium sheet (indirect solar dryer) enables high heat absorption; as a result, the heat remains trapped withing the absorber. Electric drying was carried out in a stove at 50 °C Model RIOSA HCFD-48×48, México. Figure 1 shows different solar covers types used in the drying process of *Tenebrio molitor* L.

Instrumentation

A pyranometer (CM11; 0-1400 W/m^2, ±2%, Kipp&Zonen) were placed to measure solar irradiance in the inclined plane (the tilt angle was 21°) on drying days. An ultraviolet pyranometer (SUV5-V, Maximum UVA/UVB irradiance 400 W/m^2, ±2%, Kipp&Zonen) was placed to measure de UV radiation in horizontal plane. One temperature data loggers sensors OM-HL-SP, range −30 to +70 °C (± 0.2 °C), were placed in each dryer. Measurements were recorded automatically using a data acquisition system (Agilent-34972A) every 30 s.

Experimental design

A single-factor experimental design with six levels was used, where the factor was the type of dryer; and the six levels corresponded to six different types of dryers: polycarbonate, glass, acrylic, dark polycarbonate aluminium with titanium oxide, and the electric stove at 50 °C. Each experimental test was performed in triplicate, and the data were statistically analyzed with Minitab 19. The dependent variables were the final moisture content, water activity, colour parameters, crude fat content, ash content, total protein content, crude fibre and carbohydrates.

Analytical methods

The moisture content was determined with a thermobalance (OHAUS, MB45, ±0.3%) set at 105 °C. A 3 g portion of the sample was placed in an aluminium dish at both the start and end of the test. The results were reported as a percentage.

The water activity (a_w) was measured using a Rotronic device (Higrolab C1) at 25 °C. A disposable sample cup, completely sealed, was inserted into the instrument and left for 20 min. Calibration was performed with Rotronic's verification standards.

The total protein content was assessed using the Kjeldahl method, in accordance with the NMX-F-608-NORMEX-2011, which quantifies total organic nitrogen. A 1-2 g portion of the sample was digested with concentrated sulfuric acid (analytical grade, JT Baker) to break down organic compounds. Distillation was carried out using a Kjeldahl equipment (GL-44, FERSA, Mexico), followed by titration of the distillate with 0.1 M HCl (analytical grade, JT Baker). The nitrogen percentage obtained was multiplied by a factor of 4.76 (Janssen *et al.*, 2017) to estimate total crude protein.

The crude fat content was determined through the Soxhlet gravimetric technique using an ethereal solvent. A 1-2 g sample was loaded into a cartridge and placed in the Soxhlet apparatus. Ethyl ether (150 ml, analytical grade, JT Baker) served as the extraction solvent. The process lasted 6 hours, and the fat content was calculated in accordance with the NMX-F-615-NORMEX-2018.

The ash content was analyzed via full calcination. A 3-5 g sample was weighed into a pre-measured porcelain crucible and gradually heated on a grate until the emission of smoke ceased. The resulting residue was collected for further evaluation. Ashing calculations were conducted in a muffle furnace (RHF 1600, Carbolite) at 550 °C, following the guidelines of NMX-F-607-NORMEX-2020.

The crude fibre content was analyzed according to the NMX-F-613-NORMEX-2017 method. Initially, a 1-2 g sample underwent acid digestion using hot sulfuric acid (0.1257 M, analytical grade, JT Baker). After filtration and rinsing with hot water, the residue was subjected to alkaline digestion with NaOH (0.333 M, analytical grade, JT Baker). It was then filtered again and washed with hot water until reaching a neutral pH of 7.0. The final residue was dried at 100 °C for two hours, followed by calcination at 500 °C for 1 h. All analyses were conducted in triplicate.

The total carbohydrate content was calculated using the formula described by Fikiru *et al.* (2016): Total carbohydrates (%) = 100 − (% moisture +% total protein content +% crude fat +% crude fibre +% ash content).

Colour parameters were analyzed using a high-precision colourimeter (NR60CP+). Measurements were recorded in the CIE Lab system in terms of L (lightness), a (red to green), b (yellow to blue), H (hue angle), and C (chroma or saturation). These data enabled the calculation of the colour difference (ΔE) between fresh and dried samples, along with chroma and hue angle values, following the equations provided by García-Valladares *et al.* (2023).

$$\Delta E = \left(\Delta L^2 + \Delta a^2 + \Delta b^2\right)^{\frac{1}{2}} \tag{1}$$

$$C = \sqrt{(a)^2 + (b)^2} \tag{2}$$

$$H = \arctan\left(\frac{b}{a}\right) \tag{3}$$

3 Results

Characterization of yellow mealworms

Tenebrio molitor L. had an initial moisture content of 68.34% and water activity of 0.983; colour parameters of fresh yellow mealworms were: L = 39.73, a = 8.56, b = 23.55, chroma = 25.06, and hue = 70.03 (Table 1); as seen from the results, fresh yellow mealworm tends to brown colour, due to a (red) and b (yellow) in the positive side, and the hue angle of 70° between red and yellow. In this study, the nutrient composition of yellow mealworm was 15.09% of total protein content, 5.70% of crude fat content, 4.21% of crude fibre, 0.651% carbohydrates, 0.945% of ash content and 68.34% of moisture.

Temperatures, solar and UV radiation during the drying process of yellow mealworms

Figure 2 shows the fluctuation of solar irradiance and temperature in relation to the sun's movement. The maximum solar irradiance recorded was 1079 W/m². The average temperatures inside the dryers were 60.67

TABLE 1 Characteristics of raw yellow mealworm larvae (*Tenebrio molitor L*)

Property	Mean ± SD	Property	Mean ± SD
Moisture content (% w.b)	68.34 ± 0.745	Ash content (%)	0.945 ± 0.040
Water activity	0.983 ± 0.002	*L*	39.73 ± 1.590
Total proteins content (%)	15.09 ± 0.367	*a*	8.56 ± 0.198
Crude fat content (%)	5.706 ± 0.258	*b*	23.55 ± 1.047
Crude fibre (%)	4.210 ± 0.324	Chroma	25.06 ± 1.054
Carbohydrates (%)	0.651 ± 0.240	Hue (°)	70.03 ± 0.382

L, lightness; *a*, green-red; *b*, yellow-blue.

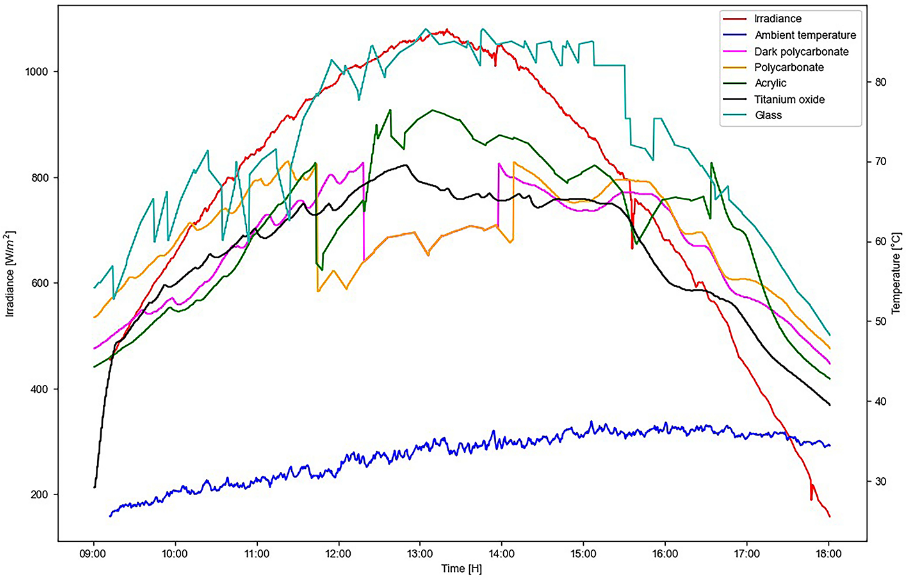

FIGURE 2 Temperature profiles and solar irradiance across different types of covers of solar dryers used during the mealworm drying (*Tenebrio molitor L*).

(polycarbonate), 72.56 (glass), 62.20 (acrylic), 59.29 (dark polycarbonate) and 58.52 °C (aluminium with titanium oxide). Under these conditions, the initial moisture content of yellow mealworms (68.34%) decreased to 2.31% in the polycarbonate dryer (240 min), 1.39% in the glass dryer (240 min), 1.32% in the acrylic dryer (240 min), 3.10% in the dark polycarbonate dryer (300 min), 5.49% in the titanium oxide dryer (360 min) and 4.16% using the electric stove (300 min) (Figure 3). Figure 4 shows the UV radiation levels inside each solar dryer. Maximum external UV radiation reached 36.28 W/m^2, while internal values were 20.11 W/m^2 (glass), 6.04 W/m^2 (acrylic), 0.38 W/m^2 (polycarbonate), and 0.18 W/m^2 (dark polycarbonate). In the titanium oxide dryer (indirect solar dryer), UV radiation was not detected.

Colourimetric analysis in dried Tenebrio molitor

Fresh yellow mealworms exhibit a brownish tone, influenced by positive values on the *a* (red) and *b* (yellow) axes, with a hue angle indicating a shade between red and yellow (Figure 5). However, their colour characteristics changed during drying. Table 2 shows a decrease in ΔL across all dryers, indicating that the samples became darker than the fresh yellow mealworms. Negative Δa and Δb values reflect reduction in redness and yellowness, respectively, while negative hue angle values suggest a shift toward a redness and less yellow appearance. The total colour difference (ΔE) is an important attribute related to consumer acceptance, with larger ΔE values generally associated with greater browning. In this study, the smallest colour variation occurred in the electric stove at 50 °C ($\Delta E = 11.43$), followed by the titanium oxide dryer ($\Delta E = 12.8$) and the acrylic dryer ($\Delta E = 14.59$). As shown in Table 2, higher colour differences were observed in solar dryers, where ultravi-

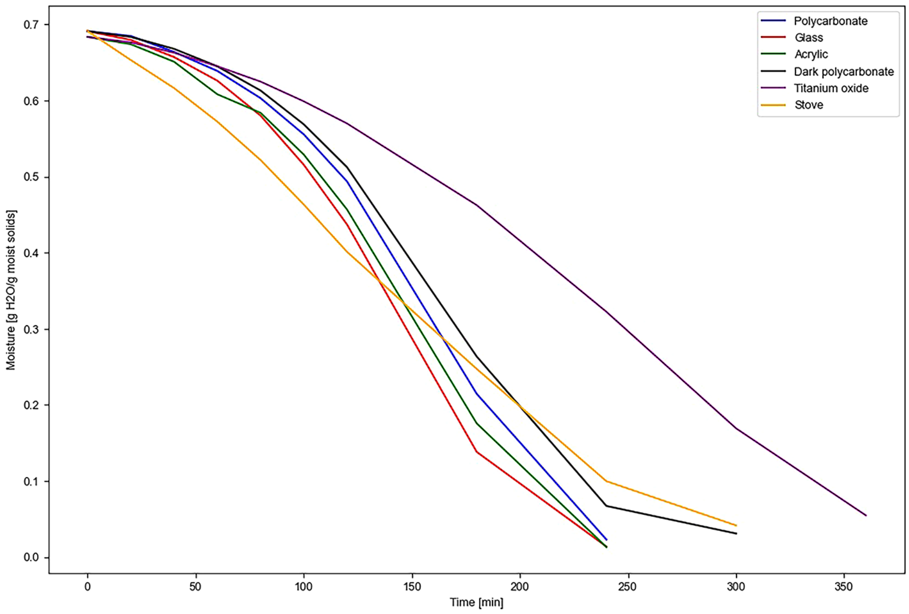

FIGURE 3 Drying curves of yellow mealworms (*Tenebrio molitor L*) using different types of covers of solar dryers.

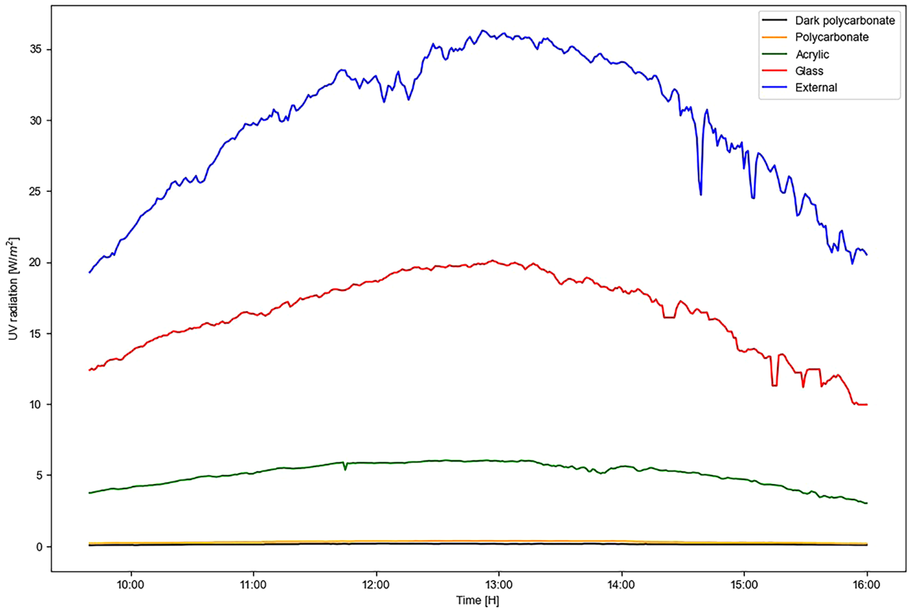

FIGURE 4 Ultraviolet (UV) radiation during the drying process of mealworms (*Tenebrio molitor L*) using different types of covers of solar dryers.

olet radiation was more intense (Figure 4). In contrast, the titanium oxide dryer and the electric stove exhibited only minor reductions in colourimetric parameters.

Proximal analysis in dehydrated yellow mealworms

As a result of removal of water, the concentration of nutrients in the product increases; therefore, the components were more concentrated in the dried sample than in the fresh mode (Table 2). The initial total protein content of yellow mealworms was 15.09%, which increased to 41.04% in samples dehydrated using a polycarbonate dryer, 40.95% with a glass dryer, 38.61% using an acrylic dryer, 38.88% with a dark polycarbonate dryer, 40.97% in a titanium oxide dryer, and 39.02% using an electric stove at 50 °C. Regarding crude fat content, it increased from 5.706 to values that ranged from 32.43 to 33.72%. The crude fibre content rose from 4.21% to a range between 5.74 and 6.11%. The same behavior was observed in carbohydrates content, it increases from 0.65% to values ranging between 1.40 and 4.83%. The concentration of ash content changed to values that ranging from 3.35 to 3.72% (Table 2).

FIGURE 5 Visual comparison of the yellow mealworm (*Tenebrio molitor L*) drying process using different types of covers of solar dryers.

4 Discussion

Characterization of yellow mealworms

According to Lenaerts *et al.* (2018) fresh *Tenebrio molitor* L. larvae have a moisture content between 59 and 68%, and a water activity of around 0.96, which makes them highly susceptible to microbiological spoilage, lipid oxidation, and both enzymatic and non-enzymatic reactions. With respect to colour, Lenaerts *et al.* (2018) reported similar colour values for fresh yellow mealworms (L = 40.49, a = 9.30, and b = 22.09), in their work, the impact of different drying methods on colour quality was reported. The chemical composition of larvae has been reported by Purschke *et al.* (2018), Kröncke *et al.* (2018, 2019), and Mariod (2020). Rearing conditions, differences in their diet, growing conditions are factors that impact on the proximal composition of yellow mealworms (*Tenebrio molitor* L.).

Temperatures, solar and UV radiation during the drying process of yellow mealworms

Baek *et al.* (2019) reported that hot-air drying of yellow mealworms at 60 °C for 6 h reduced their moisture content to 7.71%. On the other hand, Kröncke *et al.* (2019) reported a reduction in moisture content from 62.87 to 0.87% with rack oven drying, 1.70% with vacuum drying and 9.83% with freeze drying. Finally, Azzollini *et al.* (2016) reported the drying kinetics of yellow mealworms by using a forced air oven at 50, 60 and 70 °C for 450 min. Some studies focused on solar drying of insects have demonstrated the effect of UV radiation on their properties. In the study of Nyangena *et al.* (2020), solar drying of four edible insect species resulted in a slight increase in crude protein contents, ranging from 1.5 to 3.5%, depending on the species examined. The authors noted that thermal treatments may lead to a reduction in nitrogen content, potentially resulting from the loss of amides and amines or the formation of complexes with primary and secondary lipid oxidation products. However, the present findings indicated that these effects were likely superseded by other factors, such as the loss of dry matter components. Tiencheu *et al.* (2012) in the sun drying of *Rhynchophorus phoenicis* larvae significantly increased the percentage of oleic acid but it was concluded that should avoid applying prolonged drying due to the sunlight initiates oxidation reactions. In relation to the fat content of the yellow mealworm the browning substances produced during the solar drying method may produce both changes in fat content and phospholipid deprivation as seen in the results shown by Selaledi and Mabelebele (2021) where fat content was superior in the solar drying in comparison to oven and frezze drying.

Colourimetric analysis in dried Tenebrio molitor L.

Authors as Parniakov *et al.* (2022) suggest that prolonged exposure to high-temperature hot air drying can subject samples to non-enzymatic browning reactions, which may subsequently result in reduced lightness values. Usub *et al.* (2008) in the drying of silkworm pupae found that the darkness in sun drying was due to the direct exposure of the pupae surfaces to solar irradiance for a longer drying time. The observed colour variation between fresh and dried samples results from multiple factors. Lehmad *et al.* (2024) identified enzymatic browning reactions as a key contributor, where polyphenol oxidation and the subsequent formation of iron-polyphenol complexes are involved. In addition, non-enzymatic browning reactions between amino acids and reducing sugars also play a significant role in alter-

TABLE 2 Characteristics of dried yellow mealworm larvae using solar dryers with different covering materials

Property	Solar-dried *Tenebrio molitor* L.					Conventional dried (electric stove, 50 °C)
	Polycarbonate	Glass	Acrylic	Dark polycarbonate	Titanium oxide	
Drying time (min)	240	240	240	300	360	300
Moisture content (% w.b)	2.31 ± 0.983	1.39 ± 0.092	1.32 ± 0.127	3.10 ± 0.93	5.49 ± 0.134	4.16 ± 0.742
Water activity	0.566 ± 0.011a	0.448 ± 0.018b	0.282 ± 0.002c	0.277 ± 0.005c	0.477 ± 0.001b	0.478 ± 0.001b
Total protein content (%)	41.04 ± 0.728a	40.95 ± 0.581b	38.61 ± 0.457b	38.88 ± 0.522b	40.97 ± 0.413b	39.02 ± 0.467b
Crude fat content (%)	33.145 ± 0.591ab	32.959 ± 0.483ab	32.43 ± 0.457ab	33.72 ± 0.481a	33.15 ± 0.607ab	31.82 ± 0.388b
Crude fibre (%)	5.746 ± 0.579a	6.118 ± 0.522a	6.059 ± 0.530a	5.764 ± 0.520a	5.746 ± 0.514a	5.230 ± 0.410a
Carbohydrates (%)	1.404 ± 0.679c	4.098 ± 0.565ab	4.831 ± 0.829a	2.648 ± 0.327bc	1.615 ± 0.454c	3.784 ± 0.987ab
Ash content (%)	3.484 ± 0.136ab	3.725 ± 0142a	3.644 ± 0.112ab	3.359 ± 0.157bc	3.067 ± 0.085c	3.412 ± 0.108abbc
ΔL	−15.31 ± 3.902a	−14.25 ± 1.25a	−12.73 ± 3.64a	−13.3 ± 2.192a	−11.87 ± 0.318a	−10.38 ± 1.49a
Δa	−1.18 ± 0.134ab	−1.46 ± 0.714ab	−1.33 ± 0.693b	−1.19 ± 0.354ab	0.14 ± 0.509a	−1.43 ± 0.318ab
Δb	−9.74 ± 1.633a	−8.68 ± 1.761a	−7.01 ± 3.231a	−7.75 ± 2.659a	−4.8 ± 1.414a	−4.56 ± 1.386a
ΔC	−9.36 ± 1.407a	−8.57 ± 1.895a	−6.96 ± 2.638a	−7.61 ± 2.546a	−4.39 ± 1.499a	−4.77 ± 1.414a
ΔH	−2.81 ± 0.948a	−1.97 ± 0.007a	−1.35 ± 2.447a	−1.83 ± 0.856a	−1.96 ± 0.071a	−0.24 ± 0.191a
ΔE	18.19 ± 3.097ab	16.75 ± 2.044ab	14.59 ± 4.695a	15.44 ± 3.253ab	12.8 ± 0.849ab	11.43 ± 1.930b

ΔL, lightness difference; Δa, redness-greenness difference; Δb, yellowness-blueness difference; ΔC, chroma difference; ΔH, hue angle difference; ΔE, colour difference. Values are mean ± SD.

* Mean values that do not share a letter are significantly different (α = 0.05).

ing sample colour. The lower redness and yellowness values observed in Δ*a* and Δ*b* in the present study can be explained in accordance with the findings of Puangsap *et al.* (2025) during the drying of edible crickets. It was observed that sun drying requires prolonged exposure to air and sunlight at ambient temperatures, where sunlight can initiate the photo-oxidation of certain molecules. The extended drying period under aerobic conditions likely promotes lipid oxidation, which may lead to brown discolouration or reduced colour intensity in high-protein feedstuffs. Chavan *et al.* (2022) reported that foods dehydrated using indirect-type solar dryers retain better quality, as they are not directly exposed to UV radiation. Consequently, colour parameters such as: lightness, *a*, *b*, hue angle, and chroma are better preserved. In addition, the authors reported that blocking most incident UV radiation helps prevent fat oxidation, which can cause off-colours and rancidity.

Proximal analysis in dehydrated yellow mealworms

In this study, the analysis of variance (ANOVA) revealed that the total protein content of samples dehydrated using a polycarbonate dryer was significantly different compared to those dried with glass, acrylic, dark polycarbonate, titanium oxide, and electric stove dryers. Regarding crude fat content, no significant differences were observed among samples dehydrated with polycarbonate, glass, acrylic, and titanium oxide dryers; however, the dark polycarbonate dryer produced significantly different results. For fibre content, the ANOVA indicated no significant differences between the drying methods. In terms of carbohydrate content, the analysis showed that samples dried with polycarbonate and titanium oxide dryers were similar, as were those dried with a glass dryer and an electric stove at 50 °C; however, the acrylic dryer differed significantly from the other methods. Purschke *et al.* (2018) reported increases in protein and fat contents during oven drying at 80 °C for 7 h, freeze drying at 0.2 mbar for 48 h and fluidized bed drying at 55 °C for 2 h. This investigation indicated that chitin depletion resulted in a statistically significant increase in total protein content within the fine particle fractions. Additionally, the use of thermal drying may have facilitated the co-diffusion of melted fat from inner tissues (fat body) to the chitin shell during water removal, thereby leading to an elevation in chitin-associated fat levels. Selaledi and Mabelebele (2021) reported total protein contents of 50.96% in yellow mealworms dried by sun drying for 24 h, 51.45% by freeze-drying at −50 °C for 24 h, and 51.51% by oven drying at 120 °C for 1 h. By contrast, a reduction in total protein content in yellow mealworms has been reported by Kröncke *et al.* (2019) and Yan *et al.* (2023). Purschke *et al.* (2018) found that, even when studying the same species of yellow mealworms, variables such as diet, origin, instar phase, and seasonal fluctuations can lead to significant differences in nutrient composition. Additionally, processing techniques and the specific larval stage selected for analysis may affect outcomes. Other factors, including rearing conditions play a crucial role in determining the chemical and nutritional quality of yellow mealworms (Syahrulawal *et al.* 2023). In the research conducted by Shadung *et al.* (2012), the drying of African metallic wood boring beetle at 66 °C resulted in increased protein and other nutrient levels. This enhancement was attributed to improved protein digestibility, as the process unfolded polypeptide chains and made the proteins more susceptible to enzymatic digestion also the moisture removal by heat increased concentration of nutrients and made some nutrient more available. With respect to radiation the investigation of Lima *et al.* (2018), reported that macronutrients as lipids, carbohydrates, and proteins are relatively stable with doses of radiation up to 10 kGy, and regarding proteins, in thermal processing, the denaturation is less intense.

5 Conclusions

This study evaluated the impact of different solar drier covering materials on the physical and chemical properties of yellow mealworm larvae (*Tenebrio molitor* L.). Results indicated that all the solar dryers effectively reduced the moisture content of yellow mealworm larvae to levels that inhibit microbiological deterioration. However, the titanium oxide dryer (indirect dryer) and electric stove at 50 °C resulted in the least colour variation suggesting that non-exposure to UV radiation helps preserve colour as quality attribute that impact in the food acceptance. The proximal analysis revealed an increase in the concentration of the total protein content, crude fat content, crude fibre, carbohydrates, and ash content, due to water removal. The findings suggest that solar drying using a titanium oxide-coated dryer or other indirect solar dryers offers a promising alternative to traditional electric drying methods, providing a good balance between nutrient preservation, colour, and energy efficiency. By optimizing the design and materials used in solar dryers, it may be possible to further improve the quality and shelf life of dried yellow mealworms larvae, supporting their potential as a sustainable food source. The study provides valuable insights for the development of sustainable drying technologies for edible insects, particularly in regions with high solar irradiance. Overall, it was possible to demonstrate the viability of solar drying as a method for preserving the quality and nutritional value of yellow mealworms larvae, and it may serve as a reference for future studies on the drying of edible insects.

Acknowledgements

The authors hose names are listed above agree to be accountable for the content and conclusions of the article. We thank professor Víctor Gomez Espinoza for his help in the instrumentation of the direct solar dryer, José Manuel Vázquez Morales for preparing the graphs and OptiProt company, headed by Magdalena Ivonne Márquez García, for providing the raw material (*Tenebrio molitor L.*) necessary for the development of the experiments. To the project PAPIIT IN100926: Secado de productos alimentarios para zonas rurales con tecnología de secadores solares tipo invernadero.

Author contributions

Alfredo Domínguez-Niño: Writing (review, editing), methodology. Paulina Guillén-Velázquez: Investigation, experimentation, data curation. Iris Santos-González: experimentation, data analysis, investigation, writing (review). Mario Luna-Flores: Experimentation. Octavio García-Valladares: Validation, conceptualization, writing (review and editing).

Conflict of interest

The authors declare no conflict of interest.

Data availability

Data are available from the authors on request.

References

Alves, A.V., Sanjinez-Argandoña, E.J., Linzmeier, A.M., Cardoso, C.A.L. and Macedo, M.L.R., 2016. Food value of mealworm grown on *Acrocomia aculeata* pulp flour. PLoS ONE 11: e0151275. https://doi.org/10.1371/journal.pone.0151275

Azzollini, D., Derossi, A. and Severini, C., 2016. Understanding the drying kinetic and hygroscopic behaviour of larvae of yellow mealworm (*Tenebrio molitor*) and the effects on their quality. Journal of Insects as Food and Feed 2: 233-243. https://doi.org/10.3920/jiff2016.0001

Baek, M., Kim, M., Kwon, Y., Hwang, J., Goo, T., Jun, M. and Yun, E., 2019. Effects of processing methods on nutritional composition and antioxidant activity of mealworm (*Tenebrio molitor*) larvae. Entomological Research 49: 284-293. https://doi.org/10.1111/1748-5967.12363

Bogusz, R., Bryś, J., Onopiuk, A., Pobiega, K., Tomczak, A., Kowalczewski, P.Ł., Rybak, K. and Nowacka, M., 2024. The impact of drying methods on the quality of blanched yellow mealworm (*Tenebrio molitor* L.) larvae. Molecules 29: 3679. https://doi.org/10.3390/molecules29153679

Castillo-Téllez, M., Ovando, S.J.C., Lezama, Z.F. and Álvarez, D.C.M., 2019. Nut drying of India cultivated in Campeche, México through direct solar technologies and under controlled conditions. Revista Bistua Facultad de Ciencias Básicas 17: 60-69. https://doi.org/10.24054/01204211.v3.n3.2019.3566

Chavan, A. and Thorat, B., 2022. Techno-economic comparison of selected solar dryers: a case study. Drying Technology 40: 2105-2115. https://doi.org/10.1080/07373937.2021.1919141

Costa, S., Pedro, S., Lourenço, H., Batista, I., Teixeira, B., Bandarra, N.M., Murta, D., Nunes, R. and Pires, C., 2020. Evaluation of *Tenebrio molitor* larvae as an alternative food source. NFS Journal 21: 57-64. https://doi.org/10.1016/j.nfs.2020.10.001

Da Costa Rocha, A.C., De Andrade, C.J. and De Oliveira, D., 2021. Perspective on integrated biorefinery for valorization of biomass from the edible insect *Tenebrio molitor*. Trends in Food Science and Technology 116: 480-491. https://doi.org/10.1016/j.tifs.2021.07.012

Domínguez-Niño, A., Guillén-Velázquez, P., Santos-González, I., García-Valladares, O. and Vázquez-Morales, J.M., 2025. Total phenolic, flavonoid content, and antioxidant activity of dried marigold (*Tagetes erecta* L.) petals produced in a mixed-mode solar dryer. Plant Foods For Human Nutrition 80: 123. https://doi.org/10.1007/s11130-025-01366-z

Esua, O.J., Chin, N.L., Yusof, Y.A. and Sukor, R., 2019. Combination of ultrasound and ultraviolet-C irradiation on kinetics of colour, firmness, weight loss, and total phenolic content changes in tomatoes during storage. Journal of Food Processing and Preservation 43: e14161. https://doi.org/10.1111/jfpp.14161

Fikiru, O., Bultosa, G., Forsido, S.F. and Temesgen, M., 2016. Nutritional quality and sensory acceptability of complementary food blended from maize (*Zea mays*), roasted pea (*Pisum sativum*), and malted barley (*Hordium vulgare*). Food Science and Nutrition 5: 173-181. https://doi.org/10.1002/fsn3.376

García-Valladares, O., Dominguez-Niño, A., Lucho-Gómez, A.M., Jiménez-Montiel, A.G., Rodríguez-Mendoza, A.S., Castillo-Téllez, B., Luna-Flores, M. and Castillo-Téllez, M., 2024. Mixed-mode solar drying and its effect on physicochemical and colourimetric properties of zompantle (*Erythrina americana*). Plant Foods for Human Nutrition 79: 194-201. https://doi.org/10.1007/s11130-024-01147-0

García-Valladares, O., Lucho-Gómez, A.M., Montiel-Baltazar, E.A., Castañeda-Vázquez, M., Ortiz-Sánchez, C.A., Castillo-Téllez, B., Luna-Solano, G. and Domínguez-Niño, A., 2023. Effect of modified solar dryers on colourimetric and physicochemical properties of pumpkin flower (*Cucurbita maxima*). Plant Foods For Human Nutrition 78: 139-145. https://doi.org/10.1007/s11130-022-01032-8

Huang, L. and Zhang, M., 2012. Trends in development of dried vegetable products as snacks. Drying Technology 30: 448-461. https://doi.org/10.1080/07373937.2011.644648

Janssen, R.H., Vincken, J., Van Den Broek, L.A.M., Fogliano, V. and Lakemond, C.M.M., 2017. Nitrogen-to-protein conversion factors for three edible insects: *Tenebrio molitor*, *Alphitobius diaperinus*, and *Hermetia illucens*. Journal of Agricultural and Food Chemistry 65: 2275-2278. https://doi.org/10.1021/acs.jafc.7b00471

Jongema, Y., 2017. Worldwide list of recorded edible insects. Available at https://www.wur.nl/upload_mm/8/a/6/0fdfc700-3929-4a74-8b69-f02fd35a1696_Worldwide%20list%20of%20edible%20insects%202017.pdf

Kröncke, N., Böschen, V., Woyzichovski, J., Demtröder, S. and Benning, R., 2018. Comparison of suitable drying processes for mealworms (*Tenebrio molitor*). Innovative Food Science and Emerging Technologies 50: 20-25. https://doi.org/10.1016/j.ifset.2018.10.009

Kröncke, N., Grebenteuch, S., Keil, C., Demtröder, S., Kroh, L., Thünemann, A.F., Benning, R. and Haase, H., 2019. Effect of different drying methods on nutrient quality of the yellow mealworm (*Tenebrio molitor* L.). Insects 10(4): 84. https://doi.org/10.3390/insects10040084

Kumar, M., Sansaniwal, S.K. and Khatak, P., 2016. Progress in solar dryers for drying various commodities. Renewable and Sustainable Energy Reviews 55: 346-360. https://doi.org/10.1016/j.rser.2015.10.158

Lange, K.W. and Nakamura, Y., 2021. Edible insects as future food: chances and challenges. Journal of Future Foods 1: 38-46. https://doi.org/10.1016/j.jfutfo.2021.10.001

Langston, K., Selaledi, L., Tanga, C. and Yusuf, A., 2024. The nutritional profile of the yellow mealworm larvae (Tenebrio molitor) reared on four different substrates. Future Foods 9: 100388. https://doi.org/10.1016/j.fufo.2024.100388

Lehmad, M., Hidra, N., Lhomme, P., Mghazli, S., Hachimi, Y.E. and Abdenouri, N., 2024. Environmental, economic and quality assessment of hybrid solar-electric drying of black soldier fly (*Hermetia illucens*) larvae. Renewable Energy 226: 120401. https://doi.org/10.1016/j.renene.2024.120401

Lenaerts, S., Van Der Borght, M., Callens, A. and Van Campenhout, L., 2018. Suitability of microwave drying for mealworms (*Tenebrio molitor*) as alternative to freeze drying: Impact on nutritional quality and colour. Food Chemistry 254: 129-136. https://doi.org/10.1016/j.foodchem.2018.02.006

Liceaga, A.M., 2021. Processing insects for use in the food and feed industry. Current Opinion in Insect Science 48: 32-36. https://doi.org/10.1016/j.cois.2021.08.002

Lima, F., Vieira, K., Santos, M. and De Souza, P.M., 2018. Effects of radiation technologies on food nutritional quality. IntechOpen, London. https://doi.org/10.5772/intechopen.80437

Makkar, H.P.S., 2018. Review: Feed demand landscape and implications of food-not feed strategy for food security and climate change. Animal 12: 1744-1754. https://doi.org/10.1017/S175173111700324X

Mariod, A.A., 2020. Nutrient composition of mealworm (*Tenebrio molitor*). In: African edible insects as alternative source of food, oil, protein and bioactive components, pp. 275-280. Springer, Cham. https://doi.org/10.1007/978-3-030-32952-5_20

Melgar-Lalanne, G., Hernández-Álvarez, A.J. and Salinas-Castro, A., 2019. Edible insects processing: traditional and innovative technologies. Comprehensive Reviews in Food Science and Food Safety 18: 1166-1191. https://doi.org/10.1111/1541-4337.12463

Miranda, S.A. and Santos, K.G.D., 2020. Produção de cebola desidratada em secador solar convectivo de bandeja. Revista Brasileira de Ciência Tecnologia E Inovação 5: 98-111. https://doi.org/10.18554/rbcti.v5i2.3345

Muñoz-Seijas, N., Fernandes, H., López-Periago, J.E., Outeiriño, D., Morán-Aguilar, M.G., Domínguez, J.M. and Salgado, J.M., 2024. Characterization of all life stages of *Tenebrio molitor*: envisioning innovative applications for this edible insect. Future Foods 10: 100404. https://doi.org/10.1016/j.fufo.2024.100404

Mustapha, N.E.H.B., Hachem, H. and Mihoubi, D., 2026. State of the art of solar drying systems integrating energy storage materials. Solar Energy 303: 114169. https://doi.org/10.1016/j.solener.2025.114169

NMX-F-607-NORMEX-2020, 2022. Alimentos-determinación de cenizas en alimentos. DOF – Diario Oficial de la Federación. Dof.gob.mx. Available at https://dof.gob.mx/nota _detalle.php?codigo=5641716andfecha=01/02/2022#gsc.tab=0

NMX-F-608-NORMEX-2011, 2014. Alimentos-determinación de proteínas en alimentos-método de ensayo. DOF – Diario Oficial de la Federación. Dof.gob.mx. Available at https://www.dof.gob.mx/nota_detalle.php?codigo=5360486andfecha=18/09/2014#gsc.tab=0

NMX-F-613-NORMEX-2017, 2017. Alimentos-determinación de fibra cruda en alimentos. DOF – Diario Oficial de la Federación. Dof.gob.mx. Available at https://www.dof.gob.mx/nota_detalle_popup.php?codigo=5534254

NMX-F-615-NORMEX-2018, 2019. Alimentos-determinación de extracto etéreo (Método SOXHLET) en alimentos. DOF – Diario Oficial de la Federación. Dof.gob.mx. Available at https://dof.gob.mx/nota_detalle.php?codigo=5552291andfecha=08/03/2019#gsc.tab=0

Nyangena, D.N., Mutungi, C., Imathiu, S., Kinyuru, J., Affognon, H., Ekesi, S., Nakimbugwe, D. and Fiaboe, K.K.M., 2020. Effects of traditional processing techniques on the nutritional and microbiological quality of four edible insect species used for food and feed in East Africa. Foods 9: 574. https://doi.org/10.3390/foods9050574

Parniakov, O., Mikhrovska, M., Wiktor, A., Alles, M., Ristic, D., Bogusz, R., Nowacka, M., Devahastin, S., Mujumdar, A., Heinz, V. and Smetana, S., 2022. Insect processing for food and feed: a review of drying methods. Drying Technology 40: 1500-1513. https://doi.org/10.1080/07373937.2021.1962905

Puangsap, W., Pootthachaya, P., Oryza, M., Cherdthong, A., Chankitisakul, V., Tengjaroensakul, B., Phaengphairee, P. and Wongtangtintharn, S., 2025. Evaluation of the Effects of drying techniques on the physical and nutritional characteristics of cricket (*Gryllus bimaculatus*) powder for use as animal feedstuff. Insects 16: 814. https://doi.org/10.3390/insects16080814

Purschke, B., Brüggen, H., Scheibelberger, R. and Jäger, H., 2018. Effect of pre-treatment and drying method on physico-chemical properties and dry fractionation behaviour of mealworm larvae (*Tenebrio molitor* L.). European Food Research and Technology 244: 269-280. https://doi.org/10.1007/s00217-017-2953-8

Ramos-Elorduy, J., 2008. Energy supplied by edible insects from Mexico and their nutritional and ecological importance. Ecology of Food and Nutrition 47: 280-297. https://doi.org/10.1080/03670240701805074

Sacilik, K. and Elicin, A.K., 2006. The thin layer drying characteristics of organic apple slices. Journal of Food Engineering 73(3): 281-289. https://doi.org/10.1016/j.jfoodeng.2005.03.024

Secretaría de Agricultura y Desarrollo Rural, 2018. Insectos comestibles. gob.mx. Available at https://www.gob.mx/agricultura/articulos/hay-una-mosca-en-mi-sopa-insectos-comestibles-156649

Selaledi, L. and Mabelebele, M., 2021. The influence of drying methods on the chemical composition and body colour of yellow mealworm (*Tenebrio molitor* L.). Insects 12: 333. https://doi.org/10.3390/insects12040333

Shadung, N.K.G., Mphosi, M.S. and Mashela, P.W., 2012. Influence of drying method and location on proximate chemical composition of African metallic wood boring beetle, *Sternocera orissa* (Coleoptera: Buprestidae) in Republic of South Africa. African Journal of Food Science 6: 155-158. https://doi.org/10.5897/AJFS11.146

Sharma, A., Chen, C.R. and Lan, N.V., 2009. Solar-energy drying systems: a review. Renewable and Sustainable Energy Reviews 13: 1185-1210. https://doi.org/10.1016/j.rser.2008.08.015

Syahrulawal, L., Torske, M.O., Sapkota, R., Naess, G. and Khanal, P., 2023. Improving the nutritional values of yellow mealworm *Tenebrio molitor* (Coleoptera: Tenebrionidae) larvae as an animal feed ingredient: a review. Journal of Animal Science and Biotechnology 14: 2-18. https://doi.org/10.1186/s40104-023-00945-x

Tiencheu, B., Womeni, H.M., Linder, M., Mbiapo, F.T., Villeneuve, P., Fanni, J. and Parmentier, M., 2012. Changes of lipids in insect (*Rhynchophorus phoenicis*) during cooking and storage. European Journal of Lipid Science and Technology 115: 186-195.

Turck, D., Bohn, T., Castenmiller, J., De Henauw, S., Hirsch-Ernst, K.I., Maciuk, A., Mangelsdorf, I., McArdle, H.J., Naska, A., Pelaez, C., Pentieva, K., Siani, A., Thies, F., Tsabouri, S., Vinceti, M., Aguilera-Gómez, M., Cubadda, F., Frenzel, T., Heinonen, M., Marchelli, R., Neuhäuser-Berthold, M., Poulsen, M., Maradona, M.P., Siskos, A., Schlatter, J.R., Loveren, H.V., Zakidou, P., Ververis, E. and Knutsen, H.K., 2023. Safety of UV-treated powder of whole yellow mealworm (*Tenebrio molitor*) larvae as a novel food pursuant to Regulation (EU) 2015/2283. EFSA Journal 21: e08009. https://doi.org/10.2903/j.efsa.2023.8009

Usub, T., Lertsatitthanakorn, C., Poomsa-ad, N., Wiset, L., Yang, L. and Siriamornpun, S., 2008. Experimental performance of a solar tunnel dryer for drying silkworm pupae. Biosystems Engineering 101: 209-216. https://doi.org/10.1016/j.biosystemseng.2008.06.011

Yan, X., Laurent, S., Hue, I., Cabon, S., Grua-Priol, J., Jury, V., Federighi, M. and Boué, G., 2023. Quality of *Tenebrio molitor* powders: effects of four processes on Microbiological Quality and Physicochemical factors. Foods 12: 572. https://doi.org/10.3390/foods12030572