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Research Article

Comparative study of pre-drying treatment on physicochemical properties, fatty acid composition, and volatile compounds of oil extracted from dried *Tenebrio molitor* larvae

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Abstract: The present study aimed to compare the effects of different pre-drying treatments (e.g., freeze drying, microwave drying, and oven drying) on the physicochemical properties, fatty acid composition, and volatile compounds of oil extracted from dried *Tenebrio molitor* larvae. The results showed that oil from freeze-dried *T. molitor* larvae (O-FTML) was characterized by a high degree of oxidation, with significantly high acid and peroxide values ($P < 0.05$), and the highest content of saturated fatty acids ($P < 0.05$). However, oil from microwave-dried *T. molitor* larvae (O-MTML) and oven-dried *T. molitor* larvae (O-OTML) with higher iodine values showed lower oxidation ($P < 0.05$), possessed lower viscosity, and higher thermal stability ($P < 0.05$). In addition, the O-OTML group increased the proportion of unsaturated fatty acids and stimulated baking aroma, similar to that of vegetable oils. In conclusion, oven-drying may be the optimal drying treatment for oil extracted from *T. molitor* larvae.

Keywords: *Tenebrio molitor* larvae oil; pre-drying treatment; fatty acid composition; volatile compounds; oxidation

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1 Introduction

A recent survey report by the Food and Agriculture Organization of the United Nations found that the global population is expected to reach about 10 billion by 2050[1], which will lead to a rapid increase in global food demand, especially food of animal origin (mainly meat products). However, the increased demand for livestock may lead to climate change, environmental pollution, and habitat degradation[2]. Moreover, large-scale livestock production may also have negative impacts on animal health and welfare. Therefore, sustainable nutritional resources need to be developed as suitable alternatives to traditional animal-derived foods. Edible insects are gradually attracting attention as they are considered to be highly nutritious and rich in proteins, fats, and minerals needed by the human body[3].

Tenebrio molitor larvae have a short rearing cycle and a low level of environmental pollution[4], and could be a promising, convenient candidate insect for industrial-scale production. In 2021, the Commission Implementing Regulation (EU) 2021/882 authorizing the placing of dried *T. molitor* larvae on the market as a novel food, which was the first insect food to be approved in the European Union[5]. Due to their nutritional richness, *T. molitor* larvae are often used commercially as animal feed. In regions such as Asia and Africa, they may even be considered a meat substitute[6]. However, the use of *T. molitor* larvae as food additives is limited by a number of factors, notably unpleasant appearance and widespread human prejudice[7]. To overcome the above problems, *T. molitor* larvae are usually ground into powder for use[8]. However, whole *T. molitor* larvae powders contain up to 30% fat, which is poorly oxidatively stable and tends to agglomerate (caking) when added to foods as an ingredient[9–10]. Therefore, the oil needs to be separated during processing. The obtained *T. molitor* larvae oil serves as a new resource from which to produce oil-based products[11]. Research on the use of *T. molitor* larvae oil as a biodiesel feedstock has been reported[12–13]. In recent years, researchers have found that *T. molitor* larvae oil provides the second most important nutrient in *T. molitor* larvae. It contains ω-3 and ω-6 polyunsaturated fatty acids (PUFAs) comparable to those found in fish and can be easily digested[6]. Therefore, *T. molitor* larvae oil can be utilized as a valuable essential fatty acid resource in the food field. However, the application of *T. molitor* larvae oil in edible oil-based products is rarely reported.

Drying is the first step in *T. molitor* larvae processing. In this way, the potential microbial presence in larvae is reduced, and shelf life is extended, while maintaining nutritional properties and consumer acceptance. Furthermore, drying modulates larval oxidation, fatty acid retention, and volatile aroma profiles through controlled heat treatment and microstructural changes, ultimately defining their nutritional and physicochemical properties. Therefore, selecting appropriate drying technology is crucial for ensuring the nutritional value and sensory quality of *T. molitor* larvae[14]. Freeze drying, microwave drying, and oven drying are currently the most mainstream and mature drying technologies in industrial-scale production. They encompass the primary physical mechanisms of drying technology, representing low-temperature

vacuum (freeze drying), high-frequency microwave dielectric heating (microwave drying), and convective heat transfer (oven drying), respectively[15]. In industrial applications, freeze-drying is primarily used for high-end quality preservation, microwave drying for energy-efficient acceleration, and oven drying for cost control. Over the past decade, researchers have reported that all three drying treatments significantly impact the whole-meal and protein content of *T. molitor* larvae, indicating comparable efficacy. For instance, Lenaerts et al.[9] found that microwave-dried whole powder of *T. molitor* larvae had a lower brightness value (L^*). Kröncke et al.[16] investigated suitable drying treatments for *T. molitor* larvae and found that freeze drying increased protein solubility. Bogusz et al.[17] concluded that convective drying at 90 °C resulted in the highest levels of essential fatty acids with the lowest total levels of yeasts and molds in *T. molitor* larvae. However, few studies have emphasized the effect of pre-drying treatment on the quality of *T. molitor* larvae oil.

Therefore, in this paper, *T. molitor* larvae were dried using freeze-drying, microwave drying, and oven drying, respectively, from which oil was extracted from the dried *T. molitor* larvae. Physicochemical properties and fatty acid compositions were determined and characterized structurally by Fourier transform infrared (FTIR) spectroscopy, in addition to an examination of their thermodynamic and rheological properties. This study contributes to the identification of the optimal pre-drying treatment for the extraction of *T. molitor* larvae oil, which provides ideas for the application of *T. molitor* larvae oil as a novel edible oil-based product.

2 Materials and methods

2.1 Materials

Living *T. molitor* larvae were acquired from Jiarui Co., Ltd. (Heze, China) via live shipment, and samples were ensured to be in a fresh state upon arrival at the laboratory. According to the method described by Zhang et al.[18], *T. molitor* larvae were separated from impurities in the feed residues by passing them through a 20-mesh sieve before pretreatment. All other chemicals and reagents associated with the experimental process were of analytical grade.

2.2 Drying process

Blanching was applied to living *T. molitor* larvae for 40 s as described by Vandeweyer et al.[19]. After that, three different pre-drying treatments were applied to the blanched *T. molitor* larvae: freeze-drying, microwave drying, and oven drying, respectively. Ultimately, the moisture content of the *T. molitor* larvae was maintained at (3.0 ± 0.5)% for each pre-drying treatment.

Before freeze-drying, 1 000 g of *T. molitor* larvae were subdivided into four freezer trays and placed in a freeze-dryer (HFD-4, Zhengzhou Kewanda Biological Instrument Co., Ltd., Zhengzhou, China). The condenser temperature was set at –50 °C, with the process lasting approximately 48 h[16].

Before microwave drying, 1 000 g of *T. molitor* larvae were spread on a 34 cm × 32 cm × 3 cm tray, which was placed in the microwave oven (KTMC300, Shanghai Jieti Instrument Co., Ltd., Shanghai, China). The drying process was performed at a power of 850 W for 10 min[16].

Before oven drying, 1 000 g of *T. molitor* larvae were divided between two baking plates (40 cm × 36 cm × 1.5 cm) located in the center of an oven (WGL-658, Tianjin Taisite Instrument Co., Ltd., Tianjin, China). The drying process consisted of 19 h at 60 °C under ventilated conditions[20].

2.3 Preparation of oil samples

The dried *T. molitor* larvae were pelletized with a grinder (DXF-06D, Guangzhou Xiangming Machinery Equipment Co., Ltd., Guangzhou, China), and then filtered through a steel sieve (40 mesh) with a pore size of 450 μm. For oil extraction, the ground *T. molitor* larval powder was mixed with 5 g/mL of *n*-hexane and homogenized with a magnetic stirrer (LY-CJ6, Qingdao Luyang Environmental Protection Technology Co., Ltd., Qingdao, China) at 500 r/min for 30 min to enrich the fat. The mixture was centrifuged at 5 000 × *g* for 15 min at 4 °C to obtain a lipid-rich *n*-hexane supernatant. After that, the *n*-hexane in the collected supernatant was removed with a rotary evaporator (RV3-V, IKA Works GmbH & Co., Ltd., Staufen, Germany) at 60 °C[21]. In addition, the above process was repeated four times to obtain as much oil as possible. Finally, oil from freeze-dried *T. molitor* larvae (O-FTML), oil from microwave-dried *T. molitor* larvae (O-MTML), and oil from oven-dried *T. molitor* larvae (O-OTML) were obtained, respectively, by removing residual *n*-hexane with nitrogen gas[10].

2.4 Extraction yield determination

The extraction yield was derived from the mass ratio of the extracted oil to the initial dried *T. molitor* larvae samples.

2.5 pH determination

The pH of each oil sample was measured using a pH meter (PB-10, Sartorius, Germany).

2.6 Color determination

The color of the oil samples was analyzed by a color meter (ZE-7700, Nippon Denshoku, Kogyo Co., Ltd., Tokyo, Japan), and a CIELAB color space analysis was applied[9]. Before analysis, the oil sample was allowed to stand at 35 °C for 1 h. Then, 2 mL of the oil sample was placed in a cup for colour analysis[22].

2.7 Iodine value (IV), acid value (AV), peroxide value (POV), and *p*-anisidine value (*p*-AV) determination

The IV of the oil sample was measured using the Wijs method, as specified in the American Oil Chemists' Society (AOCS) 1993 method[23]. Iodine chloride undergoes an addition reaction with an unsaturated double bond, and the IV was calculated by titrating an excess of iodine molecules with 0.1 mol/L standard sodium thiosulfate solution.

The AV can represent the amount of free carboxylic acid groups in an oil, with standard titration methods being used to determine AV[24]. Briefly, 2.5 g of oil sample was dissolved in 50 mL of organic mixture solution containing ether and isopropanol (1:1, *V*/*V*), 1% (*m*/*m*) phenolphthalein solution was chosen as an indicator, and free fatty acids in the mixture were titrated with 0.1 mol/L potassium hydroxide solution.

The POV of the oil sample was measured using a modified method derived from the AOCS 2003 method[25]. Completely dissolve 2 g of oil in 30 mL of organic solution with a 2:3 volume ratio of chloroform to glacial acetic acid. In the dark, the mixture was shaken for 30 s as 1 mL of saturated potassium iodide solution was added. After 5 min of reaction, 100 mL of distilled water and 1% (*m*/*m*) potato starch solution were added to the mixture. A 0.01 mol/L sodium thiosulfate solution was used to titrate the

mixture until the blue color disappeared. POV is expressed as milliequivalents of O_2 per kilogram of oil (meq O_2/kg).

The *p*-AV of the oil sample was determined according to the modified method of the AOCS 2011 method[26]. Briefly, 0.5 g of the oil sample was placed in a 25 mL volumetric flask, and 25 mL of isooctane was added. The mixture was shaken until the oil was completely dissolved. The absorbance (A_b) of the oil solution was measured at 350 nm. Additionally, 1 mL of 0.25% (*m*/*m*) *p*-anisidine reagent and 5 mL of the diluted oil solution were mixed in the dark for 10 min. The absorbance (A_s) of the solution was then recorded at 350 nm. The *p*-AV was calculated using the following equation:

$$p\text{-AV} = \frac{25 \times (1.2 \times A_s - A_b)}{m}$$

Where *m* represents the mass of the fat sample (g).

2.8 Fatty acid composition determination

The fatty acid composition of the oil sample was analyzed using a gas chromatograph-mass spectrometer (7820A, Agilent, Santa Clara, CA, USA) equipped with a capillary column (100 m × 0.25 mm, 0.2 μm). Helium was used as a carrier gas and maintained a flow rate of 1 mL/min. The injector temperature was set at 270 °C with a split ratio of 30:1. The programmed temperature increase process was divided into three stages, running for a total of 55 min. In the first stage, the temperature was set at 100 °C with a holding time of 1 min, after which the temperature was ramped up to 190 °C at 15 °C/min with a holding time of 4 min. In the second stage, the temperature was increased to 200 °C at 1 °C/min for 15 min. In the final stage, the temperature was ramped up to a final temperature of 250 °C at a rate of 5 °C/min and held for 9 min. The mass spectrum was performed in selected ion monitoring mode with an electron collision ionization voltage of 70 eV[9]. Qualitative and quantitative analyses were performed by retention time and relative peak area percentage for each fatty acid methyl ester, respectively. In conclusion, the accuracy of the experimental method was verified by the standards of different fatty acids.

2.9 Volatile composition determination

The volatile compounds of the oil sample were quantified by headspace solid phase microextraction coupled with gas chromatography-mass spectrometry (HS-SPME-GC-MS). Briefly, 1.0 mL of oil was placed in a headspace vial (10 mL, 46 mm × 22.5 mm) with a 17.5 mm polytetrafluoroethylene septum for sealing. To reach equilibrium before testing, oil was incubated at 40 °C for 15 min. The volatile compounds at the top of the headspace vial were then extracted using SPME fibers for 30 min. Immediately, the SPME fiber was resolved in the GC injection port for 1 min. All oil samples were analyzed using HP-5MS capillary column (30 m × 0.25 mm, 0.25 μm). The analytical procedure was carried out with high-purity helium as carrier gas, maintaining a constant flow rate of 1.0 mL/min. The oven program for GC was maintained at 45 °C for 3 min, after which it was increased to 240 °C at 3 °C/min and maintained for 5 min. The MS source electron energy is 70 eV, and the mass range is *m*/*z* 35–450. The transmission line and ion source temperatures are 250 and 230 °C, respectively[27]. The NIST 08 database was referenced for identification of volatile compounds. To verify the accuracy of the results, the retention index (RI) of volatile compounds was calculated by *n*-alkane mixtures (C_8–C_{20}), which were compared to the Kovats index (KI) reported by NIST. Volatile compounds were quantified by the ratio of the extracted ionic area to a specific internal standard.

2.10 FTIR spectra determination

The chemical structure changes of oil were analyzed by an FTIR spectrometer (Nicolet iS50, Waltham, MA, USA). The dried potassium bromide was pressed into a transparent sheet under an infrared lamp, followed by a uniform application of 10 μL of the oil sample in the center of the sheet. The spectrum from 4 000–400 cm^{-1} was scanned 32 times by a spectrometer with a resolution of 4 cm^{-1}. OMNIC 32 software was used to analyze the variations in the FTIR spectra of oil[28].

2.11 Thermogravimetric analysis (TGA)

Thermal stability of oil was analyzed using a thermogravimetric analyzer (SDT Q650, Water Co., Ltd., New Castle, DE, USA). Approximately 5–10 mg of the oil sample was weighed before loading into an alumina crucible. Nitrogen at a flow rate of 50 mL/min was used as the carrier gas. The oil sample was heated from room temperature to 600 °C at a heating rate of 10 °C/min. An aluminum crucible without an oil sample as a reference. The data on oil with temperature was recorded and analyzed[29].

2.12 Differential scanning calorimetry (DSC) analysis

To assess the oxidative stability of the oil sample, DSC (DSC 300, Netzsch Scientific Instruments Trading Co., Ltd., Selb, Germany) was applied. Approximately 5–10 mg of the oil sample was weighed and placed in an aluminum crucible, using the aluminum crucible without the sample as a reference. The oil was rapidly cooled to −40 °C and held for 5 min to ensure complete crystallization, and then heated to 60 °C at 10 °C/min[27]. The melting curve of oil was recorded and analyzed with the software of the instrument.

2.13 Rheological properties measurements

The rheological properties of oil were determined using an MCR 502 rheometer (Anton Paar Co., Graz, Austria). The effects of shear rate on the viscosity of oil were analyzed. In the experiments for viscosity determination, 0.84 mL of the oil sample was taken and added to the cylinder; the instrument gap was set to 0.3 mm. The apparent viscosity versus shear rate curves were determined at 25 °C, and the range of shear rate was 0.1–100 s^{-1}[30].

In the experiments with temperature scanning, the temperature versus viscosity curves were determined at a shear rate of 50 s^{-1}, a ramp rate of 5 °C/min, and a temperature range of 5–85 °C[31].

To further investigate the rheological behavior of oil at different frequencies, the strain amplitude values were all set to 1%, and the frequency sweeps from 0.1 to 15 Hz were set at 25 °C to record the energy storage modulus (G') and loss modulus (G'')[32].

2.14 Statistical analysis

Data statistics were analyzed by IBM SPSS Statistics 26 software (SPSS Inc., Chicago, IL, USA). Statistical significance of the experimental results was calculated by one-way analysis of variance using the Duncan post-hoc test ($P < 0.05$). Final results are reported as mean ± standard deviation (SD) in triplicate.

3 Results and discussion

3.1 Effects of different drying pretreatments on the extraction yield and pH of *T. molitor* larvae oil

The extraction yield and pH of oil were shown in Table 1. It was shown that O-MTML exhibited the highest extraction yield of 28.56% ($P < 0.05$), which may be due to the rapid evaporation of

water from the *T. molitor* larvae under the action of microwaves, which resulted in damage to the cellular structure, thus favoring the mass transfer of fat. In addition, the low-pressure conditions during freeze drying, which cause oil loss accompanied by water evaporation[33], resulted in the lowest extraction yield of O-FTML ($P < 0.05$). The O-OTML had the highest pH ($P < 0.05$), which was closest to neutral. Omozuwa et al.[34] concluded that the pH of the oil was positively correlated with the IV or unsaturated fatty acid (UFA) content. It implies that O-OTML contains high UFAs, which was also verified by IV (Table 1) and fatty acid composition.

Table 1 Extraction yield, pH, color, AV, IV, POV, and *p*-AV of the oil extracted from different pre-dried *T. molitor* larvae.

Item	O-FTML	O-MTML	O-OTML
Extraction yield (%)	24.93 ± 0.42^c	28.56 ± 0.56^a	26.60 ± 0.40^b
pH	4.70 ± 0.15^c	6.61 ± 0.06^b	7.06 ± 0.14^a
L^*	8.01 ± 0.21^c	18.24 ± 0.47^b	29.39 ± 0.34^a
a^*	0.57 ± 0.37^a	−1.96 ± 0.25^b	−3.62 ± 0.60^c
b^*	8.14 ± 0.31^b	7.64 ± 0.16^b	9.85 ± 0.35^a
IV (%)	56.37 ± 0.42^c	81.49 ± 0.50^b	90.78 ± 0.23^a
AV (mg KOH/g)	9.70 ± 0.22^a	2.81 ± 0.14^b	1.50 ± 0.26^c
POV (meq O_2/kg)	3.06 ± 0.27^a	2.89 ± 0.15^a	1.93 ± 0.06^b
p-AV	2.64 ± 0.20^a	2.02 ± 0.11^b	1.20 ± 0.13^c

Note: Values are given as the mean ± SD from triplicate determinations. Values within a row marked with different lowercase superscript letters indicate statistically significant differences ($P < 0.05$).

3.2 Effects of different drying pretreatments on the color of *T. molitor* larvae oil

As shown in Table 1, changes in the color of oil which prepared via different pre-drying treatments were observed. L^* indicates lightness and darkness, which were significantly lower for O-FTML than those of O-MTML and O-OTML ($P < 0.05$). This may be because carotenoids are better retained during the freeze-drying process, resulting in a darker oil color[35]. In addition, compared to O-FTML and O-MTML, O-OTML had a lower a^* and a higher b^* with a bright yellow color, which is more acceptable to consumers as the edible oil. This is attributed to the more appropriate temperature and pressure during oven drying, which significantly reduces the solubility of the pigments in the oil[36], which is also characterized by the appearance of oil as shown in Figure 1.

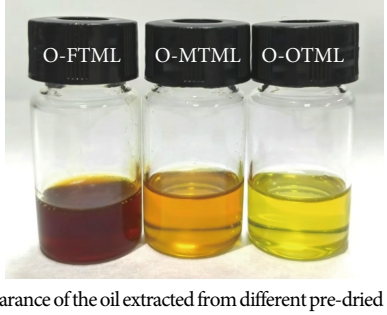

Figure 1 Appearance of the oil extracted from different pre-dried *T. molitor* larvae.

3.3 Effects of different drying pretreatments on the IV, AV, POV, and *p*-AV of *T. molitor* larvae oil

IV is an important parameter reflecting the quality of oil, which is directly proportional to the degree of unsaturation of the oil[37]. As shown in Table 1, the O-FTML had the lowest IV of all the samples at 56.37% ($P < 0.05$), indicating that its low UFA content results in a higher tendency to form solids at ambient temperatures[38]. In addition, the IV of O-MTML (81.49%) and O-OTML (90.78%) were significantly higher than those of O-FTML ($P < 0.05$), which indicates that they contained more UFAs. Gharibzahedi et al.[39] obtained an oil IV of 88.7% by drying lesser mealworms at 60 °C, which is highly comparable to that of O-OTML. Qu et al.[40] found that peanuts dried by hot air at 60 °C were extracted to obtain an oil with an IV of 96.7%, which provides a favorable edible value. This was comparable to the O-OTML, suggesting that O-OTML is more suitable for the preparation of edible oil-based products.

AV is a measurement of the total acidity of the oil, including all the fatty acids that make up the glyceride molecule, which is the main indicator of the quality of the oil[41]. AV is related to the free fatty acid content of the oil, which stimulates autoxidation reactions; the AV of the oil should not exceed the recommended threshold mentioned in Codex Alimentarius (4 mg KOH/g)[31]. As shown in Table 1, the AV of O-FTML was the highest (9.70 mg KOH/g), much higher than the recommended threshold level, which indicates that the oil has undergone oxidative degradation, which renders it inedible[17]. However, the AV of O-OTML was significantly lower than that of other treatment groups ($P < 0.05$), which may be due to inactivation of lipase in *T. molitor* larvae by prolonged high-temperature drying, which inhibited the hydrolysis of triglyceride molecules[42]. Arasakumar et al.[43] dried silkworm pupae at 85–90 °C before extracting their oil, yielding the AV of 1.966, which is slightly higher than the AV of O-OTML.

POV is also an essential indicator for evaluating the quality of oil from the point of view of oxidative sensitivity. POV is related to the rate of formation and degradation of hydroperoxides, which is strongly determined by environmental conditions such as light, oxygen, or temperature[44]. As shown in Table 1, O-FTML exhibits the highest POV (3.06 meq O_2/kg), which may be attributed to the freeze-dried process resulting in a porous structure of the product. This increases the contact area between fat and oxygen, enhancing the degree of oxidation[45]. Lee et al.[27] processed *Protaetia brevitarsis seulensis* via freeze drying, yielding extracted oil with POV of 2.50 meq O_2/kg, lower than O-FTML. Additionally, the POV of O-MTML (2.89 meq O_2/kg) was comparable to O-FTML, which may be attributed to the high-temperature and high-oxygen environment during microwave drying. It causes an unfavorable reaction with oil, leading to decomposition of hydroperoxides[38]. However, O-OTML had the lowest POV (1.93 meq O_2/kg), which may be due to the higher water activity of the oven-dried sample compared to the freeze-dried sample, thus slowing down the oxidation process[46]. Furthermore, during extended baking, the Maillard reaction in *T. molitor* larvae produces non-enzymatic browning compounds, which effectively reduce lipid oxidation[47]. Additionally, the increased levels of γ-tocopherol during baking further enhance oxidative stability[6]. At present, the POV of commercially available edible oil is in the range of 2 meq O_2/kg, and O-OTML almost meets this criterion, indicating that it possesses food value[10].

p-AV reflects the content of aldehydes (particularly 2-alkenals or 2,4-diene aldehydes) in oils by quantitatively analyzing Schiff's base formed from the reaction between *p*-anisidine and carbonyl groups in fats. It serves as a key parameter for evaluating secondary oxidation products in oils[48]. Higher *p*-AV values indicate more severe oil oxidation and a pronounced rancid taste. As shown in Table 1, *p*-AV exhibits the same trend as POV, with O-FTML displaying the highest levels of secondary oxidation products (2.64). This may result from unstable primary oxidation products readily undergoing further oxidation to form secondary products. It also further indicates that freeze-dried oil samples exhibit the highest oxidation levels[49]. Phuah et al.[49] extracted superworm oil using

hot-air drying, yielding the *p*-AV of 1.38, slightly higher than O-OTML (1.20). Choi et al.[50] subjected *T. molitor* larvae to hot-air drying at varying temperatures and observed that secondary oxidation rates increased with rising temperatures. When the temperature rose from 120 to 180 °C, the *p*-AV significantly increased from 9.53 to 59.72, far exceeding that of O-OTML. This indicates that extremely high temperatures significantly promote secondary oxidation of *T. molitor* larvae oil, whereas drying at moderate temperatures has a lesser impact on oil oxidation.

3.4 Effects of different drying pretreatments on the fatty acid composition of *T. molitor* larvae oil

The nutritional quality of insect oil depends largely on its degree of unsaturation and fatty acid composition. In this study, the effect of different pre-drying treatments on the fatty acid composition of *T. molitor* larvae oil was investigated, resulting in the detection of 17 kinds of fatty acids. As shown in Table 2, the three groups of oil contained the same major saturated fatty acids (SFAs), palmitic acid ($C_{16:0}$), stearic acid ($C_{18:0}$), and myristic acid ($C_{14:0}$), which is consistent with the findings of Keil et al.[20]. Studies have shown that regular consumption of foods containing higher levels of SFAs increases the risk of suffering from chronic diseases such as diabetes[51]. The SFA contents of O-FTML and O-OTML was 26.668% and 24.678%, respectively, higher than that of O-MTML at 22.038% ($P < 0.05$). This may be attributed to the high-temperature, short-duration nature of microwave drying, which fails to uniformly and completely inactivate all lipases[52]. Since lipases typically exhibit higher hydrolytic selectivity toward SFAs, resulting in lower SFA content[53]. Overall, the SFA content of *T. molitor* larvae oil is comparable to that of extracted oil from *Cicadatra querula* (22.8%)[51], and was lower than the raw lamb meat (43.41%)[54]. This suggests that *T. molitor* larvae oil is less likely to be the cause of some chronic diseases than raw lamb oil.

Table 2 Fatty acid composition (%) of the oil extracted from different pre-dried *T. molitor* larvae.

Fatty acid	O-FTML	O-MTML	O-OTML
$C_{6:0}$	0.429 ± 0.002	N.D.	N.D.
$C_{12:0}$	0.230 ± 0.001^b	0.226 ± 0.001^c	0.237 ± 0.001^a
$C_{13:0}$	0.058 ± 0.001	N.D.	N.D.
$C_{14:0}$	2.200 ± 0.010^b	1.940 ± 0.001^c	2.600 ± 0.010^a
$C_{15:0}$	0.237 ± 0.001^a	0.170 ± 0.001^c	0.213 ± 0.002^b
$C_{16:0}$	19.433 ± 0.058^a	16.467 ± 0.058^c	17.800 ± 0.100^b
$C_{16:1}$	1.420 ± 0.001^a	1.230 ± 0.001^c	1.387 ± 0.006^b
$C_{17:0}$	0.253 ± 0.002^a	0.191 ± 0.001^c	0.205 ± 0.001^b
$C_{18:0}$	3.710 ± 0.026^a	2.957 ± 0.006^c	3.477 ± 0.021^b
$C_{18:1n9c}$	33.167 ± 0.208^a	31.667 ± 0.058^b	30.900 ± 0.100^c
$C_{18:2n6c}$	24.833 ± 0.153^c	28.567 ± 0.058^b	39.433 ± 0.153^a
$C_{20:0}$	0.117 ± 0.001^a	0.096 ± 0.002^c	0.101 ± 0.002^b
$C_{18:3n3}$	1.083 ± 0.006^c	1.543 ± 0.006^b	2.230 ± 0.010^a
$C_{20:1}$	0.150 ± 0.001^b	0.141 ± 0.002^c	0.163 ± 0.004^a
$C_{20:2}$	N.D.	0.082 ± 0.002	N.D.
$C_{20:5n3}$	0.107 ± 0.001	N.D.	N.D.
$C_{24:0}$	0.071 ± 0.001	N.D.	N.D.
ΣSFA	26.668 ± 0.148^a	22.038 ± 0.029^c	24.678 ± 0.105^b
ΣUFA	60.749 ± 0.371^c	63.217 ± 0.101^b	74.107 ± 0.256^a
ΣMUFA	34.723 ± 0.212^a	33.035 ± 0.052^b	32.450 ± 0.09^c
ΣPUFA	26.026 ± 0.159^c	30.152 ± 0.046^b	41.657 ± 0.168^a
ΣPUFA/ΣSFA	0.976 ± 0.001^c	1.370 ± 0.001^b	1.688 ± 0.002^a
ω-6 PUFAs/*ω*-3 PUFAs	20.847 ± 0.033^a	18.503 ± 0.011^b	17.690 ± 0.110^c

Note: Values are given as the mean ± SD from triplicate determinations. Values within a row marked with different lowercase superscript letters indicate statistically significant differences ($P < 0.05$). N.D., not detected. The *ω*-6 PUFAs include $C_{18:2n6c}$, while the *ω*-3 PUFAs include $C_{18:3n3}$ and $C_{20:5n3}$.

The level of UFAs is closely related to the nutritional properties of oil, as they contain nutrients like linoleic acid and linolenic acid, which the body cannot synthesize on its own[35]. As shown in Table 2, it can be seen that *T. molitor* larvae oil contains more UFAs than SFAs, almost 60% (O-FTML) to 74% (O-OTML) of the total fatty acids, which is higher than the UFAs of animals. In addition, the oil extracted from oven-dried *T. molitor* larvae contained the highest UFA content ($P < 0.05$), which may be attributed to the higher water activity of O-OTML, and delayed the process of UFA oxidation[17]. UFA can be categorized into PUFAs and monounsaturated fatty acids (MUFAs). Specifically, the content of PUFAs is inversely proportional to the degree of oxidation in oil[9]. The PUFA content of O-OTML was significantly higher ($P < 0.05$) than that of O-FTML and O-MTML, indicating lower oxidation levels in O-OTML. This trend aligns with the oxidation characteristics of the oils presented in Table 1. Compared to microwave drying, oven drying with mild hot air (60 °C) rapidly reduces the water activity of the material while effectively inhibiting the activity of lipase and lipoxygenase. This minimizes the risk of enzymatic oxidation of PUFAs during the drying process[6]. Avoid adverse effects on PUFA preservation caused by localized overheating and pro-oxidative effects. Compared to freeze drying, oven drying induces a degree of Maillard reaction, generating compounds with antioxidant activity. These substances may partially protect oils by slowing PUFA oxidation[47]. Additionally, oven drying causes relatively minor damage to cellular structures, thereby reducing the surface area of oils exposed to oxygen[45].

Moreover, ΣPUFA/ΣSFA can be used as an essential parameter for determining the nutritional value of oil, with higher values implying less fat deposition in the body, leading to higher nutritional value[55]. The highest ΣPUFA/ΣMUFA was found in O-OTML ($P < 0.05$), which is more in line with dietary recommendations. Furthermore, PUFAs are classified as *ω*-6 PUFAs and *ω*-3 PUFAs, with the ratio of *ω*-6 PUFAs/*ω*-3 PUFAs being an important indicator of fatty acids, which plays an essential role in human health. Song et al.[56] reported that a low *ω*-6 PUFAs/*ω*-3 PUFAs ratio can reduce the secretion of inflammatory cytokines and decrease mRNA expression, thereby inhibiting the formation of foam cells and the development of atherosclerosis. O-OTML exhibited the lowest *ω*-6 PUFAs/*ω*-3 PUFAs value ($P < 0.05$), which was attributed to the fact that it contained more *α*-linolenic acid ($C_{18:3n3}$), resulting in the highest *ω*-3 PUFAs content ($P < 0.05$), resulting in a well-balanced fatty acid distribution.

3.5 Effects of different drying pretreatments on the volatile composition of *T. molitor* larvae oil

The drying process will greatly promote the oxidation of oil substances in insects, which has an important effect on the quality of oil. More particularly, the volatile compounds derived from the oxidation process represent one of the factors affecting its quality. The volatile compounds of oil extracted from different dried *T. molitor* larvae were analyzed by HS-SPME-GC-MS and are shown in Table 3. A total of 38 volatile compounds were detected, belonging to seven chemical classes, including aldehydes, alcohols, ketones, esters, acids, alkanes, and heterocycles, which are also commonly found in insects and their oil. Aldehydes are derived from the decomposition of hydroperoxides, which arise from the cleavage of secondary alkoxy. Therefore, the aldehyde content can be taken as an indicator for the oxidation level[57]. The absence of detectable aldehydes in O-OTML implies that oven drying retarded the oxidation of oil, which could be attributed to the inactivation of lipoxygenase with a protective effect on the oil[58]. Different amounts

Table 3 Volatile composition of the oil extracted from different pre-dried *T. molitor* larvae.

Compound	RI	KI	Concentration (μg/mL)			Odor description
			O-FTML	O-MTML	O-OTML	
Aldehydes						
Hexanal	802	800	1.83 ± 0.25	0.55 ± 0.14	N.D.	Green, apple, fatty, grassy, aldehydic, fresh
2-Butyl-2-octenal	1 375	1 378	14.94 ± 1.08	N.D.	N.D.	Fruity, sweet, almond, burnt sugar, cherry
Benzaldehyde	967	966	N.D.	2.45 ± 0.57	N.D.	Cherry, floral, marzipan, sharp, sweet
Alcohols						
Butyl octanol	1 854	1 853	N.D.	0.84 ± 0.28	N.D.	DNC
1-Hexanol	1 027	1 029	N.D.	2.13 ± 0.44	N.D.	Herbal, flower, fruit, green, wood
Anethol	1 285	1 284	N.D.	1.24 ± 0.29	N.D.	Sweet anise licorice
2-Methyl-1-propanol	624	622	N.D.	0.54 ± 0.12	N.D.	Ethereal, sweet
Ketones						
4-Methyl-2-hexanone	851	850	0.29 ± 0.08	N.D.	N.D.	DNC
2-Pyrrolidinone	1 045	1 046	1.71 ± 0.22	N.D.	N.D.	DNC
Cyclohexanone	895	895	8.03 ± 1.33	6.52 ± 1.13	N.D.	Minty acetone
2-Nonanone	1 094	1 090	0.68 ± 0.14	N.D.	N.D.	Fragrant, fruit, green, cheese, coconut
Acetophenone	1 066	1 065	N.D.	0.44 ± 0.02	N.D.	Aromatic, almond, nuts, fruity
2-Decanone	1 192	1 196	1.38 ± 0.32	N.D.	N.D.	Fruity, floral, fatty
Esters						
Isobutyl hexanoate	1 152	1 153	0.48 ± 0.08	N.D.	N.D.	Fruity, pineapple, green apple, peach
γ-Butyrolactone	917	916	0.88 ± 0.21	N.D.	N.D.	Caramel, fatty, creamy
γ-Hexalactone	1 055	1 056	7.62 ± 1.23^{a}	4.99 ± 1.08^{b}	1.62 ± 0.72^{c}	Acidic, cheesy, green, fruity, sweaty
γ-Nonalactone	1 364	1 362	10.88 ± 0.88	N.D.	N.D.	Rancid, sour, cheesy, sweaty
Butyl acrylate	900	902	7.45 ± 0.94^{a}	3.61 ± 0.45^{b}	2.58 ± 0.22^{c}	DNC
Methyl palmitate	1 932	1 928	7.38 ± 1.21	N.D.	N.D.	Waxy, fatty, orris
Acids						
Acetic acid	606	602	8.74 ± 1.44	N.D.	N.D.	Sharp, pungent, sour, vinegar
Propanoic acid	738	740	3.44 ± 0.87	N.D.	N.D.	Pungent, acidic, cheesy, vinegar
Butanoic acid	790	793	3.30 ± 0.24	N.D.	N.D.	Acidic, caprylic, cheesy, rancid, butter
Pentanoic acid	917	915	6.98 ± 0.28	N.D.	N.D.	Animal, sharp, acidic, cheesy, sweaty
Hexanoic acid	980	981	24.44 ± 2.88	2.33 ± 0.42	N.D.	Sour, fatty, sweat, cheesy
Alkanes						
Hexane	600	600	10.47 ± 1.23^{a}	5.46 ± 0.48^{b}	3.14 ± 0.32^{c}	DNC
Cyclohexasiloxane	1 352	1 349	0.33 ± 0.12^{b}	1.61 ± 0.45^{a}	1.56 ± 0.23^{a}	DNC
(*E*)-4-Undecene	1 083	1 084	10.66 ± 1.87	N.D.	N.D.	DNC
(*Z*)-5-Undecene	1 145	1 142	25.78 ± 2.55	N.D.	6.76 ± 0.48	DNC
D-Limonene	1 035	1 035	0.86 ± 0.27	1.29 ± 0.11	N.D.	Citric, lively, tangerine, celery
Styrene	894	892	9.71 ± 1.85	5.38 ± 1.07	N.D.	Sweet, balsam, floral, plastic
Azulene	1 298	1 299	1.22 ± 0.08^{b}	0.42 ± 0.08^{c}	2.44 ± 0.49^{a}	DNC
1-Pentadecene	1 487	1 489	3.18 ± 0.84	N.D.	N.D.	DNC
Toluene	774	773	3.39 ± 0.77	1.88 ± 0.26	N.D.	Bitter almond, glue, paint, solvent
Ethyl benzene	856	857	0.71 ± 0.11^{b}	0.75 ± 0.03^{b}	5.47 ± 0.87^{a}	DNC
p-Xylene	868	870	2.49 ± 0.68^{c}	3.36 ± 1.07^{b}	4.42 ± 1.24^{a}	Cold meat fat, metal, sweet
Heterocycles						
2,5-Dimethyl pyrazine	919	917	1.22 ± 0.28^{c}	1.93 ± 0.42^{b}	3.20 ± 0.27^{a}	Cocoa, roasted nut, roast beef, woody
2,6-Dimethyl pyrazine	910	912	1.24 ± 0.31^{b}	1.30 ± 0.21^{b}	2.78 ± 0.42^{a}	Nutty, coffee, cocoa, musty, bready, meaty
2,3,5-Trimethyl pyrazine	1 004	1 005	N.D.	0.84 ± 0.23	N.D.	Nutty, baked potato, roasted peanut

Note: Values are given as the mean ± SD from triplicate determinations. Values within a row marked with different lowercase superscript letters indicate statistically significant differences ($P < 0.05$). DNC, not detected in the library. N.D., not detected.

of aldehydes were detected in O-FTML and O-MTML, indicating that the *T. molitor* larvae were oxidized with varying degrees during both freeze drying and microwave drying. Ketones, as well as aldehydes, were associated with lipid oxidation, mainly from thermal peroxidative degradation of UFAs[59]. No ketones were detected in O-OTML, which was a result of the low level of degradation and oxidation of UFAs, and the fatty acid composition verified this results (Table 2). Since alcohols and hydrocarbons have relatively high odor thresholds, they are generally considered to have a minor impact on the characteristic aroma of oil.

Ester compounds are produced mainly by the esterification of carboxylic acids and alcohols, which have a pleasant aroma. As shown in Table 3, the loss of ester content was higher in O-OTML compared to O-FTML and O-MTML. This may be attributed to the fact that esters react with large amounts of water, which hydrolyze to alcohols or phenols during prolonged drying[60]. The higher ester content of O-FTML correlated with the lower temperature and the vacuum environment of the freeze drying process, which contributes to improved preservation of the esters. According to the experimental results, acid compounds such as

propanoic acid, acetic acid, and butanoic acid were detected in the volatile compounds of O-FTML, which has the highest total acid content. This suggests that freeze drying can effectively retain acidic volatile compounds, as was observed by Dong et al.[61]. This group odor is described as unpleasantly putrid or pungent, which contributes undesirably. Finally, some heterocyclic compounds were detected in oil extracted from different dried *T. molitor* larvae. Pyrazines are heterocyclic compounds that greatly contribute to the production of pleasing aromas in foods during the baking process, which can be described as fresh, roasted nut, beany, rum[62]. As shown in Table 3, the highest amount of pyrazine was found in O-OTML compared to O-FTML or O-MTML ($P < 0.05$), which was associated with lower amounts of lipid-oxidizing compounds[58].

3.6 Effects of different drying pretreatments on the FTIR spectra of *T. molitor* larvae oil

Specific functional groups in oil are responsible for most of the peaks and shoulders of their spectra, with the importance of FTIR spectra in the structural characterization of oil molecules deriving from the ability to attribute specific absorption bands to functional groups. The presence of the peaks was attributed to the infrared absorption of functional groups, and the response intensity of the peaks was proportional to the concentration of the functional groups present in the oil. The spectral properties of different oil samples are shown in Figure 2 and Table 4. The O-MTML and O-OTML FTIR spectra showed a small peak at 3 470 cm^{-1}, which was related to the stretching of –OH bonds present in the fatty acids, and may also be related to the absorption of water by the sample, or overtones absorbed by the C=O group of the triglycerides[37]. A peak near 3 008 cm^{-1} was observed in all spectra, and O-MTML and O-OTML showed a peak at 1 655 cm^{-1}, which could be attributed to the stretching vibration of the *cis*-olefin C=C bond present in the UFAs[63]. O-OTML showed the strongest response intensity in these bands compared to O-FTML and O-MTML, implying that O-OTML contains more ΣUFA (Table 2). The presence of SFAs leads to symmetric and asymmetric stretching vibrations of the C–H bond in the CH_2 groups. The strong peaks detected near the bands at 2 922 and 2 853 cm^{-1} for O-FTML or O-OTML belong to the saturated C–H stretching vibrational bands, which suggests that the ΣSFA concentration of O-FTML and O-OTML is higher, which was consistent with the fatty acid composition results (Table 2). Both bands were also detected in Australian palm oil with high SFA concentration, which further validated the reliability of the experimental results[63].

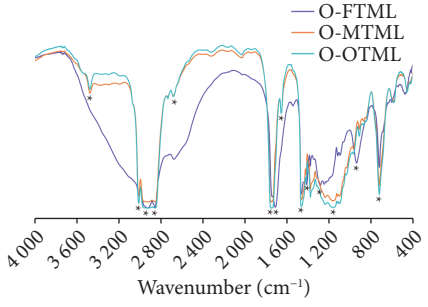

Figure 2 FTIR spectra of the oil extracted from different pre-dried *T. molitor* larvae. *Key feature peak of *T. molitor* larvae oil.

The weak peak at 2 679 cm^{-1} detected in O-MTML and O-OTML may be due to the Fermi resonance of the C=O group. The strong band at about 1 747 cm^{-1} may result from the stretching vibration of the C=O group of the triglyceride, which is usually characteristic of the C=O in ketones, aldehydes, and methyl esters present in long-chain fatty acids. All oil samples were detected with a distinct sharp peak at 1 747 cm^{-1}, implying that all oils contain a large amount of long-chain fatty acids. A small shoulder was detected in the 1 709 cm^{-1} band of the O-FTML, which could be attributed to the presence of free fatty acids, as confirmed by the highest AV of the O-FTML (Table 1). All samples exhibited strong characteristic absorption bands at 2 922, 1 464, and 722 cm^{-1}; additionally, several samples displayed prominent peaks at 2 853 and 1 159 cm^{-1}. These vibrational bands are diagnostic of triglyceride functional groups, confirming that *T. molitor* larval oil,

Table 4 Absorption bands in the FTIR spectra of the oil extracted from different pre-dried *T. molitor* larvae.

Functional group	Mode of vibration	Wavenumber (cm^{-1})		
		O-FTML	O-MTML	O-OTML
–OH	Stretching	N.D.	3 470	3 470
–C=C– (*cis*-)	Stretching	3 008	3 008	3 008
–C–H (CH_2)	Stretching (asymmetric)	2 922	2 922	2 922
–C–H (CH_2)	Stretching (symmetric)	2 853	N.D.	N.D.
–C=O	Stretching	N.D.	2 679	2 679
–C=O (ester)	Stretching	1 747	1 747	1 747
–C=O (acid)	Stretching	1 709	N.D.	N.D.
–C=C– (*cis*-)	Stretching	N.D.	1 655	1 655
–C–H (CH_2, CH_3)	Bending (scissoring)	1 464	1 464	1 464
–C–H (CH_3)	Bending (symmetric)	1 377	1 377	1 377
–C–O, –CH_2–	Stretching, bending	N.D.	1 159	1 166
–C–O	Stretching	1 118	N.D.	N.D.
–HC=CH– (*trans*-)	Bending out of plane	939	N.D.	N.D.
–HC=CH– (*cis*-)	Bending out of plane	N.D.	914	914
–$(CH_2)_n$–, –HC=CH– (*cis*-)	Bending (rocking)	7 22	7 22	7 22

Note: N.D., not detected.

like most edible oils, is predominantly composed of triglycerides[30]. The band between 1 290 and 1 040 cm^{-1} is characteristic of fatty acids. The band around 1 159 cm^{-1} may be the C–O bond stretching or CH_2 bending vibration of aliphatic esters, which was thought to be the fingerprint of C–O stretching of triglycerides in long-chain fatty acids[64]. The degree of peak response is proportional to the CH_2 content in the oil and the length of the fatty acid carbon chain. The strongest degree of response was observed for O-OTML, indicating the highest methylene content with the longest fatty acid carbon chain. Moreover, the strongest vibrational peak of O-OTML at 722 cm^{-1} carbon chain backbone also confirmed that O-OTML fatty acids possess the longest carbon chain[65]. In addition, only O-FTML was detected with an absorption peak at 939 cm^{-1}, which was characteristic of trans fatty acids, and neither O-MTML nor O-OTML was detected[66].

3.7 Effects of different drying pretreatments on the thermal stability of *T. molitor* larvae oil

The thermal stability of *T. molitor* larvae oil was determined by TGA, which includes a differential thermogravimetric (DTG) curve in addition to the typical TGA mass loss curve (Figure 3). The DTG curve is the first-order derivative form of the TGA curve, which refers to the weight loss rate of the sample as the temperature is increased, which is used primarily to differentiate between stages of the reaction[67]. As shown in Figures 3a and b, the pyrolysis of O-FTML and O-MTML was divided into two decomposition stages (stages I and II), and both decomposition and volatilization processes occur successively. Stage I is critical to the thermal stability of oil, and the degradation of UFAs commenced at this stage. Thereby, this temperature was also referred to as the onset temperature, which is positively correlated with the thermal stability of oil[31]. The onset temperatures for O-FTML and O-MTML were 233.12 and 348.62 °C, respectively, which means that O-FTML exhibits poor thermal stability. In stage I, the major loss of mass is mainly due to the degradation of organic substances (including triglycerides) and the decomposition of PUFAs[31]. The weight of O-FTML decreased to 26.81% at the maximum rate of 1.00 %/min, and the temperature reached 379.01 °C, resulting in 67.81% weight reduction. Whereas, the weight of O-MTML decreased 81.31% at the maximum rate of 2.00 %/min, when the temperature reached a higher 447.49 °C. Results indicate that the onset temperature of O-MTML is significantly higher than that of O-FTML. Based on fatty acid analysis, O-MTML exhibits a lower total SFA content (22.038%) and a higher total UFA content (63.217%). Simultaneously, the linoleic acid ($C_{18:2n6c}$) content (28.567%) in O-MTML was significantly higher than that of O-FTML. Typically, PUFAs are more prone to oxidation due to the presence of double bonds. However, TGA revealed that O-MTML exhibited a higher initial decomposition temperature. This may be attributed to the rapid molecular vibrations during microwave processing, which could induce oxidative cross-linking of some fatty acids or interactions with other matrix components (proteins), forming more stable structures and thereby enhancing thermal stability[68]. Additionally, the faster decline rate of O-MTML, as well as the higher mass loss, may be due to its higher concentration of PUFAs and low molecular weight triacylglyceric acids, which have a faster thermal decomposition rate than SFAs and MUFAs. This was also consistent with studies of fatty acid composition (Table 2). In stage II, more organic matter and carbon continued to be released from the oil[11]. O-FTML is completing the decomposition process at a maximum mass reduction rate of 0.52 %/min, and O-MTML is completing the decomposition process at a slightly lower rate (0.47 %/min), resulting in a mass reduction of 24.67% and 12.20%, respectively. O-FTML exhibited greatly higher mass reduction rates than O-MTML in the second stage, which can be attributed to the higher concentration of SFAs in O-FTML compared to O-MTML. The second stage typically corresponds to the degradation initiation of more recalcitrant components in oils (highly oxidized polymers or glycerol backbone). Compared to O-FTML, O-MTML exhibited higher temperatures and slower rates during the second stage. This may be attributed to microwave treatment inducing Maillard reactions or the formation of lipid-protein complexes, which retard the thermal decomposition process[69].

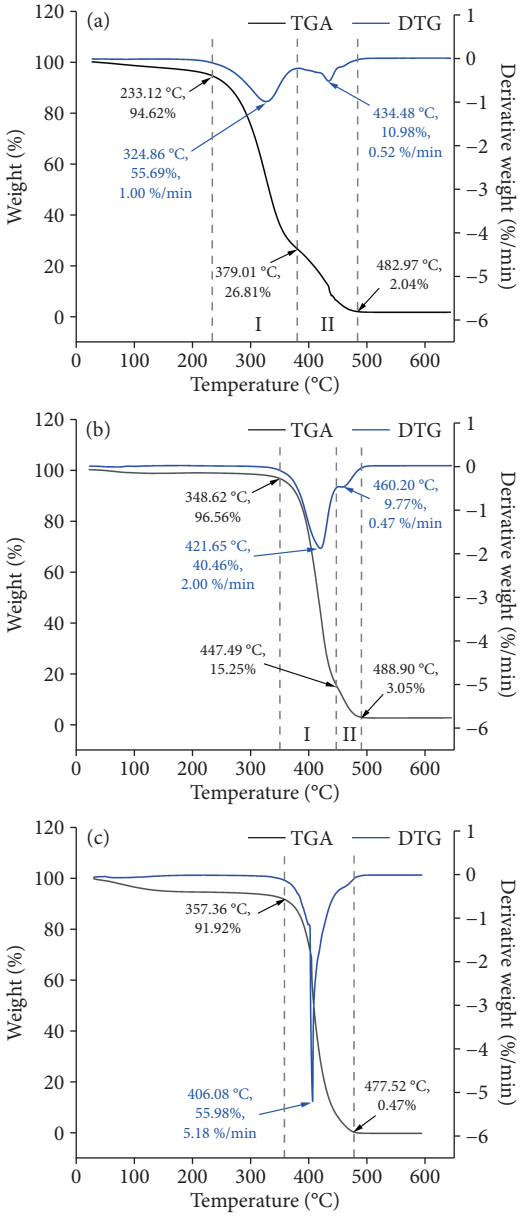

Figure 3 TGA and DTG profiles of the oil extracted from different pre-dried *T. molitor* larvae. (a) O-FTML, (b) O-MTML, and (c) O-OTML.

As shown in Figure 3c, the decomposition process of O-OTML can be roughly regarded as a stage. The initial decomposition temperature was 357.36 °C, indicating excellent thermal stability. At this stage, the maximum O-OTML rate reached 5.18 %/min, and the end temperature was only 477.52 °C, while the mass had dropped to 0.47%. The most distinctive feature of the fatty acid composition of O-OTML is an exceptionally high linoleic acid ($C_{18:2n6c}$) content (39.433%) and the highest total UFA content (74.107%). Compared to O-FTML and O-MTML, the high UFA content in O-OTML paradoxically elevated the initial decomposition temperature of the oil sample. This may result from the slow oven drying process, which enhances the orderly arrangement of fatty acid molecules and strengthens intermolecular forces (van der Waals forces). Disrupting this structure requires greater energy input, leading to the highest initial decomposition temperature. Furthermore, the pyrolysis of O-OTML can be described as a fast and stable process, which has also been found in the thermal degradation behavior of commercial soybean oil and olive oil[67]. The single, sharp decomposition peak suggests that oven-dried oils may exhibit greater compositional homogeneity, with most lipids decomposing synchronously within a narrower temperature range. In addition to the difference in SFA concentration leading to different pyrolysis stages of O-OTML compared to the other two groups, the presence of other impurities in O-FTML and O-MTML can also interact with the oil and affect the pyrolysis process, such as phospholipids, metals, minerals, etc.[70].

3.8 Effects of different drying pretreatments on the thermal behavior of *T. molitor* larvae oil

DSC melt curves can be used to quickly and directly evaluate the degree of deterioration in oil, which is critical for determining the thermal quality characteristics of *T. molitor* larvae oil[71]. The DSC melting curves of different oil samples were displayed in Figure 4. The melting point range of O-FTML was relatively wide, with two distinct melting peaks observed at −5.21 and 27.16 °C, respectively. This may be due to differences in triglyceride composition, with both high melting triglyceride and a large amount of low melting triglyceride[38], which also caused O-FTML to appear as a viscous semi-solid-like at room temperature (20 °C), rather than liquid-like. Compared to the two well-separated melting peaks observed in O-FTML, O-MTML showed overlapping melting peaks in a wide temperature range, including one main melting peak at −7.14 °C and other small peaks at −12.84 °C, indicating that a recrystallisation process has taken place. Recrystallisation is a process by which crystallised triacylglycerol is transformed into a more stable form or becomes a different crystal at a higher melting temperature, and is generally attributed to the presence of polycrystalline triglyceride with the lowest melting stability[22]. However, although O-MTML showed overlapping peaks, its melting point range indicated that it appeared liquid-like at room temperature, which was also consistent with the observed lipid state (Figure 1). As shown in Figure 4, compared to O-FTML and O-MTML, the O-OTML consisted of only one sharper and narrower peak (−10.29 °C), indicating a small melting range. This might be due to the relatively lower viscosity of O-OTML, and the effect of the centrifugal purification process was more pronounced, resulting in fewer impurities and purer O-OTML. Huang et al.[29] also found that the DSC thermograms of purified catfish oil exhibited narrower and sharper peaks compared to the unpurified fish oil, resembling the peak characteristics of O-OTML. Furthermore, as with O-MTML, O-OTML is liquid at room temperature.

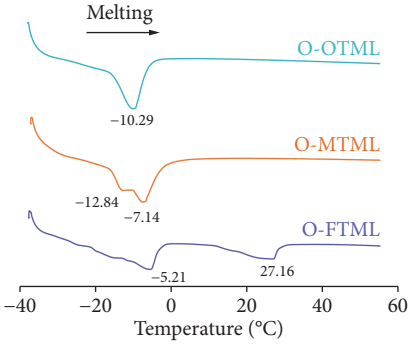

Figure 4 DSC melt curves of the oil extracted from different pre-dried *T. molitor* larvae.

3.9 Effects of different drying pretreatments on the rheological properties of *T. molitor* larvae oil

Lipids possess unique rheological properties, which greatly contribute to the textural attributes and organoleptic properties of food products. Figure 5a shows the viscosity versus shear rate curve of *T. molitor* larvae oil, which is a macroscopic representation of the flow properties and can characterize the degree of response to shear within the fat. The viscosity of O-FTML decreased sharply with increasing shear rate and exhibited an obvious shear-thinning behavior, which indicates that the O-FTML is an obvious pseudoplastic fluid (non-Newtonian)[72]. This phenomenon was relatively common and important in the industrial production of pressed oil[73]. However, at low shear rates (< 1 s^{-1}), O-FTML showed a tendency to increase and then decrease viscosity, which is called the "viscosity wrap-around peak", which may be attributed to the fact that the time of the sampling point in the low-shear region is too short, and the sample has not reached the steady state. The viscosity of O-MTML and O-OTML decreased slightly with the increase of shear rate, and their viscosities almost stabilized when the shear rate exceeded 10 s^{-1}, which means that O-MTML and O-OTML realized the transition from non-Newtonian to Newtonian fluid when the shear rate exceeded 10 s^{-1}[66]. Overall, at the same temperature, the viscosity of oil was in the order of O-FTML > O-MTML > O-OTML, which was related to the fatty acid composition (Table 2). When the PUFA content in the oil increases, the rigid structure of the oil decreases, the viscosity of the oil decreases, and the fluidity increases[74].

To further investigate the dependence of viscosity on temperature, temperature scans were performed on the oil, and the results are shown in Figure 5b. The viscosities of all three samples showed a decreasing trend as the temperature increased, which was due to the higher thermal motion between molecules at higher temperatures, which reduced the intermolecular forces and made the flow between them easier, and reduced the viscosity[75]. The viscosity of O-MTML and O-OTML showed an almost linear pattern of decreasing viscosities as the temperature increased, whereas the curve for O-FTML was clearly divided into two segments. This was because during the process of warming up, O-FTML undergoes a phase transition. The inflection point of the curve can be taken as the melting point, which represented the temperature at which the phase transition of O-FTML occurs (27.46 °C), and was extremely similar to the melting point predicted by DSC (Figure 4). In addition, the viscosity of O-FTML was lower than that of O-MTML and O-OTML as the temperature continued to increase after the phase transition occurs.

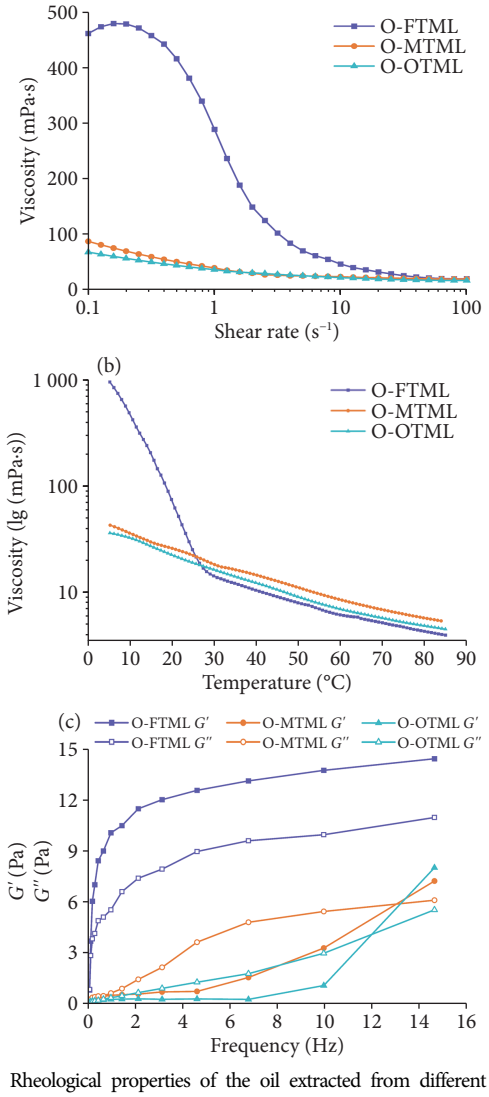

Figure 5 Rheological properties of the oil extracted from different pre-dried *T. molitor* larvae. (a) Viscosity scan curves, (b) temperature scan curves, and (c) frequency scan curves.

To evaluate the viscoelasticity of oil, frequency scans were performed, as shown in Figure 5c. The G' and G'' are two viscoelastic parameters that characterize the strength of the oil. The G' value is related to the elasticity (solid-like), while the G'' value is associated with the viscosity (fluid-like). The samples exhibit solid behavior characteristics when the G' value is larger than the G'' value, while the samples exhibit distinct fluid behavior characteristics when the G'' value is larger than the G' value. Among the three oil samples, O-FTML always had the highest G' and G'' values, indicating the highest viscosity and best stability[32]. In addition, as the frequency increases, the G' value of O-FTML was always greater than the G'' value, exhibiting solid-like behavior and failing to produce significant flow behavior[76]. As shown in Figure 5c, O-MTML and O-OTML had a higher G'' than G' in the low frequency interval, which will result in low mechanical strength and high viscous strength, making the samples flow better, and will also exhibit the typical characteristics of non-Newtonian fluids[77–78]. However, as the frequency increases, the G' of the O-MTML and O-OTML dominated and exhibited the characteristics of solid behavior.

4 Conclusion

The *T. molitor* larvae have been recognized as a sustainable food resource to replace traditional animal-based foods, but there has been relatively little research into the by-product of their processing—*T. molitor* larvae oil. Therefore, this research mainly assessed the effects of different pre-drying treatments on the quality profile of oil extracted from the dried *T. molitor* larvae. The results showed that O-MTML and O-OTML had lower AV, POV, and viscosity, significantly improved melting point and pyrolysis temperature compared to O-FTML. In addition, O-OTML retains more ω-3 PUFAs (particularly α-linolenic acid), which provides better nutritional quality and potential as an edible oil. In this study, O-OTML was found to be effective in reducing the amount of unpleasant carboxylic acid volatile compounds and producing more baking aroma, unlike O-FTML, which has a distinct pungent and acidic flavor. Additionally, during the freeze drying process, *T. molitor* larvae may produce trans fatty acids, resulting in O-FTML that do not achieve the expected high nutritional quality. In conclusion, these results help to confirm oven drying as the optimal pre-drying treatment before extracting *T. molitor* larvae oil, which provides a theoretical basis for the future development and utilization of *T. molitor* larvae oil for industrialization. However, this study was limited to the properties of oil itself. In the future, the focus should be on the utilization and development of *T. molitor* larvae oil as an edible oil-based product, which is analyzed and evaluated for its bioavailability in terms of intestinal digestion and absorption.

Conflicts of interest

The authors declared that they have no conflicts of interest in this work.

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Author contributions

Zihan Xu: Methodology, investigation, writing-original draft; Xin Li: Data curation, methodology; Yutong Liu: Investigation, software, methodology; Chuan'ai Cao: Software, resources; Baohua Kong: Visualization, resources; Hongwei Zhang: Data curation, validation; Qian Liu: Conceptualization, funding acquisition, supervision, writing-review & editing; Fengxue Zhang: Software, investigation, validation, visualization.

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