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Defatting method shapes nutritional quality, oxidative stability, and techno-functional properties of *Rhynchophorus phoenicis* larvae

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Abstract

Aim: In the context of increasing global demand for protein, edible insects are gaining attention as a sustainable food source. *Rhynchophorus phoenicis* larvae, a promising edible insect, are rich in proteins and lipids. However, their high lipid content limits food applications and stability. This study evaluated defatting methods on nutritional, techno-functional, and physicochemical properties of *R. phoenicis* larvae powders and oils.

Methods: Cooking-pressing, hexane, hexane:isopropanol, and ethanol defatting methods were investigated. Parameters included macronutrient composition (moisture, carbohydrates, lipids, proteins, ash), techno-functional properties such as water absorption capacity (WAC), oil absorption capacity (OAC), and emulsifying capacity (EC), as well as physicochemical indices including acid value (AV), peroxide value (PV), anisidine value (AnV), and TBARS.

Results: Defatted powders obtained using hexane and the hexane–isopropanol mixture showed the highest protein contents, reaching 77.63 ± 1.10 g/100 g and 71.86 ± 0.54 g/100 g, respectively. Cooking–press defatted powder exhibited the highest EC (66.70 ± 2.89%), while ethanol-defatted powder showed the highest OAC (3.11 ± 0.09 mL/g). WAC varied significantly depending on the extraction solvent, with the hexane–isopropanol mixture yielding the highest value (1.49 ± 0.05 mL/g) and ethanol-defatted powder the lowest (1.10 ± 0.02 mL/g). Physicochemical indices of *R. phoenicis* powders remained below critical thresholds, indicating good quality. In contrast, oils extracted by hexane and hexane:isopropanol showed elevated primary oxidation indices, requiring antioxidant protection and optimized storage conditions for long-term stability.

Conclusions: Defatting method influences the nutritional, physicochemical, and techno-functional properties of *R. phoenicis* larvae.

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Keywords

defatting, nutritional properties, oxidation indices, *Rhynchophorus phoenicis* larvae, techno-functional properties

Introduction

Global food insecurity affects approximately 2.3 billion people worldwide, with a particularly high burden in Africa [1, 2]. In this context, the identification of sustainable and nutrient-dense protein sources is essential [3]. Edible insects have emerged as a promising alternative due to their high nutritional value and lower environmental footprint compared to conventional livestock [4–6]. Their consumption is already widespread, particularly in Africa and Cameroon, where entomophagy is culturally accepted Cameroon [7–9].

Among these, *Rhynchophorus phoenicis* larvae (African palm weevil) are widely consumed and commercially traded in Cameroon [10–12]. They are characterized by high lipid (≈ 21.4 g/100 g fresh weight) and protein contents (8.2 g/100 g), as well as valuable micronutrients [13, 14]. However, their high lipid content, while nutritionally advantageous, can compromise oxidative stability and reduce shelf life of derived products [10, 15–17]. Consequently, defatting is a critical processing step to improve the stability and functionality of insect-based ingredients.

Defatting can be achieved through various techniques that differ significantly in terms of extraction efficiency and environmental impact [18–22]. Mechanical methods, such as cooking-pressing, offer a solvent-free alternative, although their extraction yields are often limited [23]. In contrast, organic solvent extraction remains the industrial gold standard for exhaustive lipid recovery [24, 25]. Hexane is traditionally preferred for its high affinity for neutral lipids [18]. Due to its highly hydrophobic nature, it interacts very little with the polar residues exposed on the surface of globular proteins in aqueous or semi-hydrated media. It thus limits major conformational changes, often preserving a higher degree of protein nativeness compared to alcoholic solvents [26]. In contrast, ethanol—a polar protic solvent—can disrupt hydrogen bonds and hydrophobic interactions within protein molecules, leading to partial unfolding, denaturation, and aggregation, reducing the surface area available for water binding [27, 28]. This ethanol-induced denaturation has been documented in *Acheta domesticus* and *Gryllus bimaculatus* protein preparations [25, 28]. Furthermore, from a green chemistry and food safety perspective, alternative green solvents, such as ethanol, ethyl acetate, isopropanol, are emerging as promising bio-based substitutes for lipid extraction in insect such as *Tenebrio molitor* [29, 30], *Hermetia illucens* [23], *G. bimaculatus* [25], *A. domesticus* [28]. Each of these solvants is likely to differentially impact the nutritional, physicochemical, and techno-functional properties of the resulting products. Recent studies on defatted *R. phoenicis* powders have shown that those obtained via cooking-pressing [15, 31] or solvent extraction using hexane [10], exhibit interesting functional properties, such as water and oil absorption capacities and emulsion stability. While a growing body of literature has characterised the effects of defatting on insect ingredient properties for *H. illucens* [22, 23], *G. bimaculatus* [25], *T. molitor* [30], and *A. domesticus* [28], comparative studies involving multiple simultaneous defatting methods applied to *R. phoenicis* larvae remain limited. To the best of our knowledge, no study has yet compared cooking-pressing, hexane, ethanol, and a hexane:isopropanol mixture in a single controlled experiment on this species. We hypothesise that (i) non-polar solvents (hexane, hexane:isopropanol) will achieve greater lipid removal and protein concentration than polar solvents and mechanical methods; (ii) ethanol will induce partial protein denaturation, reducing WAC and EC; and (iii) cooking-pressing will better preserve the structural integrity of functional proteins, yielding superior emulsifying properties despite lower lipid extraction efficiency. Given these considerations, this study aims to evaluate the effect of various defatting techniques on the nutritional, physicochemical, and techno-functional characteristics of *R. phoenicis* larvae.

Materials and methods

Sample collection and pre-processing

Live *R. phoenicis* larvae (2.5 kg) were purchased from a local agri-preneur and transported to the Biochemistry Laboratory at the University of Douala. Upon arrival, the larvae were subjected to a 24-hour fasting period to ensure complete evacuation of intestinal contents. Subsequently, the larvae were thoroughly washed and rinsed multiple times with distilled water to remove external impurities. To inhibit enzymatic activity and prevent thermal degradation of sensitive compounds, the larvae were sacrificed by blanching in boiling water (100°C) for 3 min, followed by immediate immersion in an ice-water bath. After cooling, the larvae were drained using a sterilized sieve. The processed larvae were then divided into two batches: A 0.5 kg aliquot was reserved for solvent-free extraction (cooking-pressing), while the remaining 2.0 kg were designated for solvent-based defatting procedures.

Preparation of reduced-lipid powders from *R. phoenicis* larvae

The solvents used for defatting were purchased from Merck: n-hexane (Cat. No. 104374, CAS 110-54-3), ethanol (Cat. No. 100983, CAS 64-17-5), and isopropanol (Cat. No. 101040, CAS 67-63-0).

Solvent-free defatting by cooking-pressing

The cooking-pressing procedure was adapted from Ngono et al. with minor modifications [31]. Cleaned and blanched *R. phoenicis* larvae (0.5 kg) were pre-heated in a stainless steel vessel at 50°C for 35 min. This step aimed to partially reduce the moisture content and decrease lipid viscosity to facilitate subsequent mechanical extraction. The heated larvae were wrapped in a sterile cotton cloth and subjected to manual mechanical pressing until no further liquid phase (oil and residual water) was expelled. The resulting defatted cakes were then dried in a ventilated oven at 45°C for 72 h to achieve a constant weight. The extracted oil was collected and stored at –20°C for further analysis.

Defatting using hexane (H) or ethanol (E)

The defatting procedure was adapted from L'Hocine et al. with slight modifications [27]. Previously dried *R. phoenicis* larvae were ground using a domestic blender to obtain a homogeneous paste. For solvent extraction, 250 g of larval paste were mixed with either hexane (1:1, *v*/*w*) or ethanol (1:2, *v*/*w*). The mixtures were stirred on a magnetic stirrer for 30 min at room temperature to facilitate lipid solubilization. Following agitation, the mixtures were allowed to settle for phase separation. The supernatant containing the solvent–oil fraction was carefully decanted, and the residual defatted cakes were collected. The defatted cakes were dried in a ventilated oven at 45°C for 72 h to ensure complete removal of residual solvent. The extracted oil was recovered and concentrated using a rotary evaporator under reduced pressure to remove solvent traces. The oil was then stored in amber glass bottles, tightly sealed and protected from light, air, and heat at −20°C until further analysis.

Defatting using hexane:isopropanol mixture (HIP)

Defatting with a hexane:isopropanol mixture was performed as described previously [32]. This binary hexane:isopropanol solvent system was used to improve lipid extraction efficiency by combining the non-polar affinity of hexane for neutral lipids with the ability of isopropanol to disrupt lipid–protein interactions and solubilise more polar lipid fractions, as previously described [33]. Dried larvae were first ground into a homogeneous paste as described above. A total of 184 g of larval paste was homogenized for 30 s with 184 mL hexane and 368 mL isopropanol (1:2, *v*/*v*). The mixture was subsequently incubated in a water bath at 50°C for 15 min to enhance lipid extraction. The suspension was centrifuged at 3,000 rpm for 10 min, and the supernatant was filtered through filter paper. The pellet was subjected to a second centrifugation under identical conditions. An additional 61.5 mL of hexane:isopropanol mixture was added to the pellet prior to centrifugation to maximize lipid recovery. The solvent–oil phase was separated from the solid residue. The resulting defatted cakes were dried at 45°C for 72 h to ensure complete solvent removal. The extracted oil was concentrated using a rotary evaporator under reduced pressure and stored in tightly sealed amber glass bottles at −20°C until further analysis.

After drying, all defatted cakes from different extraction methods were ground for approximately 5 min using a ROYAL SWISS blender (Sop-43796-110) and uniformly sieved through a 0.64 mm mesh to ensure a consistent maximum particle size across all treatments, thereby minimizing variations in surface area that could otherwise bias the evaluation of techno-functional properties. The final samples were stored in airtight containers at –20°C until further characterization.

Proximate composition analysis

The proximate composition of defatted *R. phoenicis* powders was determined using standardized methods. Moisture content was determined by drying the samples at 103°C until a constant weight was achieved using NF V04-401 standard method [34]. Crude protein content was determined via the Kjeldahl NF V04-407 standard method [35], which involved acid digestion, distillation, and titration of total nitrogen; a conversion factor of 6.19, was applied to calculate the protein percentage [14]. This factor is specific to *R. phoenicis* and accounts for the presence of non-protein nitrogen, particularly from chitin, which would lead to overestimation if the standard factor of 6.25 were used. Total lipid content was quantified using a Soxhlet apparatus (HWS-26, 1008748, Japan) with n-hexane as the extraction solvent for 12 h, following NF V04-402 standard method [36]. Ash content was determined gravimetrically by incinerating the samples in a muffle furnace at 550°C for 24 h using NF V04-404 standard method (AFNOR, 2001). Finally, total carbohydrate content was estimated by difference using the following formula:

$$Total\ Carbohydrates\ (\%) = 100 - (\%Protein + \%Lipids + \%Ash + \%Moisture)$$

The energy value was calculated using the Atwater coefficients: 16.2 kJ (4 kcal)/g for proteins and carbohydrates, and 37.62 kJ (9 kcal)/g for lipids [37].

Physicochemical analysis

Acid value (AV)

The AV of the extracted oils was determined according to the international standard [38]. Briefly, 1 mL of powder extract or 1 g of oil (m) was weighed into a 250 mL Erlenmeyer flask, and 100 mL of neutralized 95% ethanol was added. After adding two drops of 1% phenolphthalein as a colorimetric indicator, the mixture was titrated against a 0.1 N potassium hydroxide (KOH) solution. The titration was continued until a faint pink coloration persisted for at least 10 s, and the volume of titrant consumed ($V1$) was recorded. A blank titration ($V0$) was performed under identical conditions. The AV, expressed in mg·KOH/g of sample, was calculated using the following equation:

$$AV\ (mg \cdot KOH\ /\ g\ oil) = \frac{(V1 - V0)\ \times 56.1\ \times N}{m}$$

where $V1$: volume of KOH used for the sample (mL); $V0$: volume of KOH used for the blank (mL); N: normality of the KOH solution (mol/L); 56.1: relative molecular mass of KOH (g/mol); m: mass of the test portion (g).

Determination of peroxide value (PV)

The PV was determined according to the standard spectrophotometric method of IDF 74 A:1991 [39]. Briefly, 50 mg of the sample was weighed into a 10 mL glass test tube, followed by the addition of 9.8 mL of a chloroform/methanol solvent system (7:3 *v*/*v*). The mixture was homogenized by shaking for 2–4 s. Subsequently, 50 µL of 30% (*w*/*v*) aqueous ammonium thiocyanate was added and shaken for 2–4 s, after which 50 µL of an aqueous ferrous chloride solution (0.5%) was introduced. The final mixture was shaken for 2–4 s and incubated in the dark at room temperature for 5 min. The absorbance was measured at 500 nm using a spectrophotometer against a reagent blank. PV results were expressed as milliequivalents of active oxygen per kilogram of sample (meq·O_2/kg).

The PV was calculated using the following equation:

$$PV\ (meq \cdot O_2\ /\ kg\ powder) = \frac{(A_s - A_b)\ \times k}{55.84\ \times m}$$

where PV: peroxide value (meq·O_2/kg); A_s: sample absorbance; A_b: blank absorbance; k: slope obtained from the calibration curve (value provided: 38.40); m: mass of the sample (g); 55.84: molar mass of iron (g/mol) (often part of a constant factor in this calculation).

Determination of thiobarbituric acid reactive substances (TBARS)

The TBARS value was determined according to a previously described spectrophotometric method [40]. One gram of the sample was weighed into a 10 mL test tube and homogenized with a 0.1% (w/v) aqueous trichloroacetic acid (TCA) solution. To this mixture, 1 mL of 0.375% (w/v) thiobarbituric acid (TBA), 1 mL of 15% (w/v) TCA, and 1 mL of 0.25 N hydrochloric acid (HCl) were sequentially added. The samples were vortexed and subsequently incubated in a water bath at 95°C for 30 min to facilitate color development. After cooling to room temperature, the mixture was centrifuged, and the absorbance of the supernatant (aqueous phase) was measured at 532 nm using a spectrophotometer against a reagent blank. The TBARS index was expressed as mg of malondialdehyde (MDA) equivalents per kg of sample, calculated as follows:

$$TBARS\,(mg\ MDA\ /\ kg) = \frac{\left(A_s - A_b\right) \times 10^{-2} \times VTCA\ \times 2\ \times Meq}{1.56\ \times m}$$

where A_s: sample absorbance; A_b: blank absorbance; VTCA: volume of trichloroacetic acid (mL); Meq: equivalent molar mass (or a conversion factor); m: mass of the sample (g); 1.56: molar extinction coefficient of the MDA-TBA complex (typical value).

Determination of p-anisidine value (p-AnV)

The p-AnV was determined using a standard method ISO 6885, 2016 [41]. Briefly, 4.0 g of the sample was weighed into a 25 mL volumetric flask, dissolved, and diluted to volume with isooctane. The absorbance of this solution (A_b) was measured at 350 nm using a spectrophotometer (CGOLDENWALL UV-Visible Spectrophotometer) against an isooctane blank. Subsequently, 5 mL of the sample solution was transferred to a test tube, while 5 mL of isooctane was added to a second tube to serve as a reference. To each tube, 1 mL of p-anisidine solution (0.25% w/v in glacial acetic acid) was added and vortexed. After 10 min of incubation at room temperature in the dark, the absorbance of the sample (A_s) was measured at 350 nm against the reference tube. The p-AnV was calculated using the following equation:

$$\text{p - A n V} = \frac{25 \times \left(1.2A_s - A_b\right)}{m}$$

where A_s: absorbance of the lipid solution after reaction with p-anisidine; A_b: absorbance of the initial lipid solution; m: mass of the sample (g).

Technofunctional properties analysis

Determination of water absorption capacity (WAC)

The WAC was determined according to a modified centrifugal method [42]. Briefly, 0.1 g of *R. phoenicis* larva powder was mixed with 1.0 mL of distilled water in a graduated centrifuge tube. The suspension was agitated for 30 s and then centrifuged at 4,000 rpm (approximately 2,200× g) for 40 min at room temperature. After centrifugation, the supernatant was carefully decanted, and the volume of the retained water was recorded. WAC was expressed as the volume of water absorbed per unit weight of the sample (mL/g) according to the following equation:

$$WAC\,(mL\,/\,g) = \frac{Initial\ volume\ of\ Water\,(mL) - Volume\ of\ supernatant\,(mL)}{Mass\ of\ Rhynchophorus\ phoenicis\ larva\ powder\,(g)}$$

Determination of oil absorption capacity (OAC)

The OAC of the *R. phoenicis* larva powder was determined according to a modified centrifugal method [42]. Briefly, 0.1 g of the sample was mixed with 1.0 mL of refined palm oil in a graduated centrifuge tube. The mixture was agitated for 30 s and subsequently centrifuged at 4,000 rpm (approximately 2,200× g) for 40 min. Following centrifugation, the oily supernatant was carefully decanted, and the volume of the oil retained by the sample was recorded. The OAC was expressed as the volume of oil absorbed per gram of sample (mL/g) and calculated using the following equation:

$$OAC\,(mL/g) = \frac{Initial\ volume\ of\ oil\,(mL) - Volume\ of\ supernatant\,(mL)}{Mass\ of\ Rhynchophorus\ phoenicis\ larva\ powder\,(g)}$$

Determination of emulsifying capacity (EC)

The EC was determined according to a previously described method [43]. Briefly, the sample was dispersed in distilled water to obtain a 1% (w/v) concentration. A 10 mL aliquot of this dispersion was then homogenized with 10 mL of vegetable oil using a high-speed homogenizer at 16,000 rpm for 1 min. The resulting emulsion was centrifuged at 3,000 rpm for 5 min. The volume of the emulsified layer was recorded, and the EC was calculated as the percentage of the total volume occupied by the emulsion layer using the following equation:

$$EC(\%) = \frac{V_e}{V} \times 100$$

where V_e: volume of the emulsified layer (mL); V: total volume of the mixture in the centrifuge tube (mL).

Statistical analysis

All experiments were performed in triplicate, and the results are expressed as mean ± standard deviation (SD). Data were subjected to a one-way analysis of variance (ANOVA) to evaluate the effect of different defatting methods on the nutritional (moisture, lipids, proteins, carbohydrates, and ash), techno-functional (OAC, WAC, EC), and physicochemical (PV, p-AnV, TBARS) properties of the samples. The homogeneity of variances was verified using Levene's test prior to ANOVA. Significant differences between means were determined using Tukey's post-hoc multiple comparison test at a significance level of $p < 0.05$. All statistical analyses and graphical representations were performed using GraphPad Prism software version 8.2 (GraphPad Software Inc., San Diego, CA, USA).

Results

Effect of defatting on proximate composition and lipid extraction yield

Table 1 highlights the effect of defatting methods on the proximate composition of *R. phoenicis* larvae powders. Comparative analysis reveals that hexane (HDP) exhibits the highest solvent power, reducing the residual lipid content to its lowest level (11.03 ± 0.73 g/100 g DW). This extraction efficiency is correlated with the maximum concentration of protein (77.63 ± 1.10 g/100 g DW) and ash content (6.30 ± 0.12 g/100 g DW), which can be attributed to a relative concentration effect resulting from lipid removal. Conversely, the cook-press process (CPDP) proved to be the least effective for lipid extraction, generating a powder characterized by a high carbohydrate content (50.00 ± 0.33 g/100 g DW) at the expense of protein content (21.56 ± 0.28 g/100 g DW). This is likely due to the absence of solvent-mediated lipid solubilisation and limited mechanical oil recovery. The use of ethanol (EDP) for degreasing results in significant lipid retention (27.09 ± 0.27 g/100 g DW), giving this powder the highest energy density (525.87 kcal/100 g DW), reflecting its lower affinity for non-polar lipids compared to hexane. Although the hexane:isopropanol mixture (HIPDP) offers a compelling alternative with a competitive protein content (71.86 ± 0.54 g/100 g DW), it remains slightly less efficient than pure hexane. The ash content varied significantly among the treatments. Hexane (HDP) showed the highest content (6.30 ± 0.12 g/100 g DW), while ethanol (EDP) had the lowest (2.46 ± 0.14 g/100 g DW). Cook-press process (CPDP) and hexane:isopropanol mixture (HIPDP) exhibited intermediate values (4.50 ± 0.19 g/100 g DW and 5.32 ± 0.10 g/100 g DW, respectively). The moisture content was lowest for ethanol (EDP) (7.37 ± 0.48 g/100 g FW) and highest for cook-press process (CPDP) (15.60 ± 0.25 g/100 g FW). Hexane (HDP) and hexane:isopropanol mixture (HIPDP) showed relatively lower moisture contents, at 14.60 ± 0.37 g/100 g FW and 10.10 ± 0.06 g/100 g FW, respectively. The total energy of the powders was also affected by the defatting process. Ethanol (EDP) presented the highest energy value, at 525.87 kcal/100 g DW. Cook-press process (CPDP) showed an energy value of 501.66 kcal/100 g DW. Hexane (HDP) and hexane:isopropanol mixture (HIPDP) displayed lower energy values, 446.61 kcal/100 g DW and 429.58 kcal/100 g DW, respectively, which is consistent with the reduction in lipid content. From a nutritional standpoint, hexane (HDP) and hexane:isopropanol mixture (HIPDP) powders constitute the most promising matrices for the protein fortification of diets.

However, while hexane remains the industrial benchmark for efficiency, its environmental toxicity and increasing regulatory constraints are shifting research toward bio-based solvents. Isopropanol and ethanol, despite lower extraction efficiency under the tested conditions, represent safer and more sustainable technological alternatives.

Table 1. Effect of defatting methods on the macronutrient composition and lipid extraction yield of *Rhynchophorus phoenicis* larvae.

Defatting treatment	CPDP	EDP	HDP	HIPDP
Water content (g/100 g FW)	15.60 ± 0.25[d]	7.37 ± 0.48[a]	14.60 ± 0.37[c]	10.10 ± 0.06[b]
Lipids (g/100 g DW)	23.94 ± 0.26[c]	27.09 ± 0.27[d]	11.03 ± 0.73[a]	13.57 ± 1.02[b]
Proteins (g/100 g DW)	21.56 ± 0.28[a]	60.45 ± 0.15[b]	77.63 ± 1.10[d]	71.86 ± 0.54[c]
Ash (g/100 g DW)	4.50 ± 0.19[b]	2.46 ± 0.14[a]	6.30 ± 0.12[d]	5.32 ± 0.10[c]
Carbohydrates (g/100 g DW)	50.00 ± 0.33[d]	10.03 ± 0.45[c]	4.94 ± 1.48[a]	9.23 ± 1.12[b]
Energy value (kcal/100 g DW)	501.66	525.87	429.58	446.61
Lipid extraction yield (%)	9	7.2	24	14

Values are expressed as mean ± standard deviation (n = 3). One-way analysis of variance (ANOVA) followed by Tukey's post-hoc test was used for comparisons. For a given defatting treatment, within the same line, values followed by different letters are significantly different (Tukey, $p < 0.05$). HIPDP: hexane:isopropanol defatted powder; HDP: hexane-defatted powder; EDP: ethanol-defatted derived powder; CPDP: cook-press defatted powder; FW: fresh weight; DW: dry weight.

Lipid extraction yield varied significantly depending on the defatting method. Hexane extraction (HDP) showed the highest efficiency (24%), followed by the hexane:isopropanol mixture (HIPDP, 14%), while mechanical pressing (CPDP, 9%) and ethanol extraction (EDP, 7.2%) were less effective. This trend may be attributed to the strong affinity of non-polar solvents for neutral lipids, whereas polar solvents such as ethanol exhibit limited solubilisation capacity for triglycerides. The lower yield observed in mechanical pressing likely reflects incomplete oil release due to matrix retention effects.

Effect of defatting on physicochemical properties of *R. phoenicis* larvae powders

Table 2 presents the physicochemical stability indicators of *R. phoenicis* larvae powders following various defatting treatments. The results reveal statistically significant variations ($p < 0.05$) across all oxidation and hydrolysis parameters, highlighting the direct impact of solvent choice and extraction method on the physicochemical quality of *R. phoenicis* larvae powders. The lowest AVs were observed in hexane (HDP) and hexane:isopropanol mixture (HIPDP) samples (0.01 ± 0.00 mg·KOH/g powder), indicating superior hydrolytic stability induced by non-polar solvents, likely due to reduced residual moisture and limited enzyme activity in solvent-treated samples. Conversely, the EDP (ethanol) sample exhibited the highest AV (0.11 ± 0.01 mg·KOH/g powder), suggesting either a higher release of free fatty acids or the co-extraction of acidic compounds by this polar solvent, which may reflect both enhanced lipid hydrolysis and the co-extraction of polar acidic compounds. The primary oxidation state was marked by a significant increase in the PV for the hexane:isopropanol mixture (HIPDP) treatment (3.97 ± 0.17 meq·O_2/kg powder), while cook-press process (CPDP) and ethanol (EDP) processes maintained minimal levels (≤ 0.85 meq·O_2/kg). These low values for pressing and ethanol extraction demonstrate effective preservation against peroxide formation during the initial phase of oxidation, possibly due to milder processing conditions and the presence of residual antioxidant compounds. Analysis of secondary oxidation products revealed that hexane treatment (HDP) induced the most advanced degradation, with a p-AnV peaking at 3.56 ± 0.88 and a maximum TBARS content (0.32 ± 0.02 mg·MDA/kg powder), which may result from increased exposure of unsaturated lipids to oxygen following extensive lipid removal. In contrast, ethanol (EDP) provided the highest degree of protection against secondary oxidation (0.12 ± 0.01 mg·MDA/kg powder). These data suggest an inverse correlation between lipid extraction efficiency and oxidative stability: Although non-polar solvents (hexane and hexane:isopropanol mixture) optimize the defatting of the matrix, they appear to increase its vulnerability to oxidation. On the other hand, the cook-press process (CPDP) and ethanol extraction (EDP) more effectively limit the generation of secondary products, suggesting better long-term preservation of the powders' chemical quality.

Table 2. Effect of defatting methods on the physicochemical properties of *Rhynchophorus phoenicis larvae* powders.

Defatting treatment	AV (mg·KOH/g powder)	PV (meq·O_2/kg powder)	p-AnV	TBARS (mg·MDA/kg powder)
CPDP	0.05 ± 0.01^{b}	0.62 ± 0.22^{a}	0.93 ± 0.08^{b}	0.23 ± 0.03^{b}
EDP	0.11 ± 0.01^{c}	0.85 ± 0.11^{a}	1.25 ± 0.09^{c}	0.12 ± 0.01^{a}
HDP	0.01 ± 0.00^{a}	1.74 ± 0.31^{b}	3.56 ± 0.88^{d}	0.32 ± 0.02^{c}
HIPDP	0.01 ± 0.01^{a}	3.97 ± 0.17^{c}	0.39 ± 0.06^{a}	0.22 ± 0.02^{b}

Values are expressed as mean ± standard deviation (n = 3). One-way analysis of variance (ANOVA) followed by Tukey's post-hoc test was used for comparisons. Within the same column, values followed by different letters are significantly different (Tukey, $p < 0.05$). AV: acid value; PV: peroxide value; p-AnV: p-anisidine value; TBARS: thiobarbituric acid reactive substances; HIPDP: hexane:isopropanol defatted powder; HDP: hexane-defatted powder; EDP: ethanol-defatted derived powder; CPDP: cook-press defatted powder.

Effect of defatting on physicochemical properties of lipids extracted from *R. phoenicis* larvae

Table 3 presents the physicochemical stability indicators of *R. phoenicis* lipids according to the extraction methods employed. Statistical analysis reveals significant differences across all parameters, demonstrating the impact of solvents and thermomechanical processes on the chemical quality of the oils. The AV remains low for all samples, with values ranging from 0.00 ± 0.00 mg·KOH/g lipid (CPO) to 0.05 ± 0.01 mg·KOH/g lipid (hexane extraction and ethanol extraction, HO and EO). These results reflect excellent hydrolytic stability of the triglycerides, suggesting effective inactivation of endogenous lipases by preliminary thermal treatments (cooking) or an absence of residual moisture that would otherwise promote hydrolysis. The primary oxidation state is marked by significant disparities. Hexane extraction (HO) generates the highest level of alteration (17.30 ± 0.99 meq·O_2/kg lipid), which may reflect an increased sensitivity of unsaturated fatty acids during solvent evaporation or a low affinity of hexane for natural antioxidants (tocopherols, phenols). Conversely, ethanol extraction (EO) displays the lowest value (1.54 ± 0.75 meq·O_2/kg lipid), suggesting either improved initial antioxidant protection or rapid decomposition of primary oxidation products. Analysis of secondary degradation products reveals an inverse profile for the ethanol extraction (EO) sample, which exhibits the highest p-AnV (11.50 ± 0.56). This result indicates that, although the PV is low, the hydroperoxides initially formed in the ethanol-extracted oil have undergone advanced decomposition into secondary carbonyl compounds. In contrast, oil obtained by cook-pressing (CPO) and hexane extraction (HO) maintain the lowest p-AnVs (1.07 ± 0.32 and 1.34 ± 0.12, respectively), reflecting a less advanced stage of oxidation. Although organic solvents (hexane and ethanol) offer superior extraction yields, they appear to exacerbate auto-oxidation phenomena compared to the mechanical process. Cook-pressed oil (CPO) stands out as the most stable matrix, displaying an optimal balance between hydrolytic stability and resistance to oxidative degradation.

Table 3. Effect of different defatting methods on the physicochemical properties of lipids from *Rhynchophorus phoenicis* larvae.

Defatting treatment	AV (mg·KOH/g lipid)	PV (meq·O_2/kg lipid)	p-AnV
CPO	0.00 ± 0.00^{a}	5.05 ± 0.80^{b}	1.07 ± 0.32^{a}
HO	0.05 ± 0.01^{c}	17.30 ± 0.99^{d}	1.34 ± 0.12^{a}
EO	0.05 ± 0.01^{c}	1.54 ± 0.75^{a}	11.50 ± 0.56^{c}
HIPO	0.01 ± 0.00^{b}	14.40 ± 1.08^{c}	8.70 ± 0.13^{b}

Values are expressed as mean ± standard deviation (n = 3). One-way analysis of variance (ANOVA) and Tukey's post-hoc test were used for comparisons. Within the same column, values followed by different letters differ significantly (Tukey, $p < 0.05$). CPO: cook-pressed oil; HO: hexane-extracted oil; EO: ethanol-extracted oil; HIPO: hexane:isopropanol extracted oil; AV: acid value; PV: peroxide value; p-AnV: p-anisidine value.

Effect of defatting on technofunctional properties of *R. phoenicis* larvae powder

Table 4 illustrates the impact of different defatting methods on the techno-functional properties of powders derived from *R. phoenicis* larvae. Significant differences ($p < 0.05$) were observed in WAC, OAC, and EC depending on the defatting method used. The powder defatted with a hexane:isopropanol mixture (HIPDP) exhibited the highest WAC, reaching 1.49 ± 0.05 mL/g powder. It was followed by the cold-pressed defatted powder (CPDP), with a WAC of 1.38 ± 0.07 mL/g powder. The lowest WAC value was recorded for the

ethanol-defatted powder (EDP), at 1.10 ± 0.02 mL/g powder. This finding suggests that the hexane:isopropanol mixture (HIPDP) method is the most effective in preserving or enhancing WAC, whereas ethanol defatting may cause a more pronounced alteration of hydrophilic components, possibly due to protein denaturation or aggregation affecting water-binding sites. Regarding OAC, ethanol-treated samples (EDP) showed the highest value (3.11 ± 0.09 mL/g powder), significantly higher ($p < 0.05$) than those obtained for the hexane-defatted powder (HDP) (1.48 ± 0.04 mL/g powder) and hexane:isopropanol mixture (HIPDP) (1.54 ± 0.05 mL/g powder). This result indicates that ethanol promotes better interaction with the residual lipid phase, in contrast to non-polar solvents (hexane and hexane:isopropanol), which, due to their higher lipid extraction efficiency, tend to limit this phenomenon. Regarding EC, the highest value was measured for cold-pressed defatted powder (CPDP) (66.70 ± 2.89%), followed by hexane:isopropanol mixture (HIPDP) (53.30 ± 2.89%) and hexane-defatted powder (HDP) (50.00 ± 0.00%). Ethanol-treated samples (EDP) exhibited the lowest EC (40.00 ± 8.66%). The superior EC performance of cold-pressed defatted powder (CPDP) suggests that this process better preserves the structural integrity of emulsifying proteins, whereas ethanol defatting appears to impair these functional properties.

Table 4. Effect of defatting methods on the techno-functional properties of *Rhynchophorus phoenicis* larvae powders.

Treatment	WAC (mL/g powder)	OAC (mL/g powder)	EC (%)
CPDP	1.38 ± 0.07^{bc}	2.48 ± 0.08^{b}	66.70 ± 2.89^{c}
EDP	1.10 ± 0.02^{a}	3.11 ± 0.09^{c}	40.00 ± 8.66^{a}
HDP	1.33 ± 0.09^{b}	1.48 ± 0.04^{a}	50.00 ± 0.00^{bc}
HIPDP	1.49 ± 0.05^{c}	1.54 ± 0.05^{a}	53.30 ± 2.89^{b}

Values are expressed as mean ± standard deviation ($n = 3$). One-way analysis of variance (ANOVA) followed by Tukey's post-hoc test was used for comparisons. Within the same column, values followed by different letters are significantly different (Tukey, $p < 0.05$). WAC: water absorption capacity; OAC: oil absorption capacity; EC: emulsion capacity; HIPDP: hexane:isopropanol defatted powder; HDP: hexane-defatted powder; EDP: ethanol-defatted derived powder; CPDP: cook-press defatted powder.

Discussion

The results obtained highlight the effect of the defatting method on the nutritional composition, the physicochemical properties of the powders and extracted oils, as well as on the techno-functional properties of the powders from *R. phoenicis* larvae. The polarity of the solvents used (non-polar hexane, polar ethanol, and the mixed hexane:isopropanol solvent) strongly influences these variations.

Defatting strategy as a key driver of protein concentration modulation in *R. phoenicis* larvae powders

The lipid content of the powders varied considerably depending on the defatting method. The powder obtained using ethanol (EDP) retained the highest lipid content (27.09 ± 0.27 g/100 g DW), indicating a lower extraction efficiency compared to hexane (11.03 ± 0.73 g/100 g DM) or the hexane:isopropanol mixture (13.57 ± 1.02 g/100 g). This observation is consistent with the predominance of non-polar lipids (about 97% triglycerides) in the larvae [13], which are less efficiently extracted by polar solvents. Similar results reported for edible insects (*T. molitor*, *Alphitobius diaperinus*, *A. domesticus* and *Blaptica dubia*) have shown that mixtures of polar and non-polar solvents are more effective in extracting both polar and non-polar lipids and facilitate the recovery of lipids complexed with proteins [19]. The cooking-pressing method also showed low lipid extraction efficiency, yielding a lipid content of 23.94 ± 0.26 g/100 g DW (CPDP). Low extraction efficiency was also observed in the black soldier fly, *H. illucens* [23].

In correlation with lipid reduction, the protein content increased, ranging from 21.56 ± 0.28 to 77.63 ± 1.10 g/100 g DW. The hexane (HDP) and hexane:isopropanol mixture (HIPDP) powders showed the highest protein contents, 77.63 ± 1.10 and 71.86 ± 0.54 g/100 g, respectively. The elevated protein content observed in hexane (HDP) is primarily a relative concentration effect resulting from the exhaustive removal of the lipid fraction, rather than an absolute increase in protein mass. The ethanol (EDP) powder exhibited a lower protein content (60.45 ± 0.15 g/100 g DW) than the two previous powders, probably due to its

relatively higher lipid content compared to hexane (HDP) and hexane:isopropanol mixture (HIPDP) powders. This result confirms that the efficiency of extraction or defatting strongly depends on the method and the nature of the solvent used and its ability to solubilize the lipids present in the food matrix [19, 25, 28].

The cold-pressed defatted powder (CPDP) exhibited the lowest protein content (21.56 ± 0.28 g/100 g DW), indicating its low efficiency, probably because the larvae were not ground beforehand, which limits lipid release [15, 31]. This contrasts with hexane (HDP), hexane:isopropanol mixture (HIPDP), and ethanol (EDP) powders, where grinding facilitates the release of lipids trapped within cellular structures [10, 13]. Studies conducted on *R. phoenicis* and other insect species have shown that defatting with organic solvents allows a better concentration of the protein fraction in insect powders compared to pressing methods [23]. Overall, defatting of the larvae makes it possible to obtain protein-rich powders of *R. phoenicis*, representing a promising nutritional resource, particularly for addressing protein deficiencies in Africa.

The carbohydrate contents showed an inverse trend, being highest in the cold-pressed defatted powder (CPDP) (50.00 ± 0.33 g/100 g DW), compared to ethanol (EDP) (10.03 ± 0.45 g/100 g DW), hexane (HDP) (4.94 ± 1.48 g/100 g DW), and hexane:isopropanol mixture (HIPDP) (9.23 ± 1.12 g/100 g DW). This increase in carbohydrates is likely due to the proportional decrease in lipids, a phenomenon where the removal of lipids concentrates proteins and carbohydrates, as previously described [10, 23].

Moisture content, crucial for the stability of food products, ranged from 7.37 ± 0.48 to 15.60 ± 0.25 g/100 g FW. Ethanol (EDP) recorded the lowest value, while cold-pressed defatted powder (CPDP) showed the highest. These values are higher than those obtained with *H. illucens* powders, defatted by mechanical pressing and ethanol, which had moisture contents of 5.20 and 7.01 g/100 g of powder, respectively [23]. These values also exceed the moisture content limits (1–5 g/100 g) set by EU regulations regarding Novel Foods (Regulation (EU) 2021/1975; Regulation (EU) 2022/169; Regulation (EU) 2022/188; Regulation (EU) 2023/58). This legislative framework governs the introduction of insects into human consumption in Europe by imposing rigorous technical specifications to ensure food safety [44–47]. Cold-pressed defatted powder (CPDP), with a moisture content (15.60 g/100 g) that significantly exceeds the limits set by European Novel Food regulations, may exhibit a water activity conducive to microbial growth as well as chemical degradation during prolonged storage. Consequently, an additional drying step to achieve a moisture content below 5 g/100 g is essential before considering cold-pressed defatted powder (CPDP) for commercial food applications. This represents a process optimisation opportunity to be explored in future formulation studies.

Ash content, an indicator of mineral richness, was highest for hexane (HDP) (6.30 ± 0.12 g/100 g), followed by hexane:isopropanol mixture (HIPDP) (5.32 ± 0.10 g/100 g) and cold-pressed defatted powder (CPDP) (4.50 ± 0.19 g/100 g). These values are comparable to those of defatted *G. bimaculatus* powders [25], lower than those of defatted *H. illucens* and *A. domesticus* powders [23, 28], and higher than those previously obtained for *R. phoenicis* [17, 31]. These results confirm that these *R. phoenicis* larvae powders can be good sources of minerals. The highest energy values were observed for ethanol (EDP) (525.87 kcal/100 g) and cold-pressed defatted powder (CPDP) (501.66 kcal/100 g), due to their residual lipid contents.

Low oxidative degradation and compliance with Codex standards in defatted *R. phoenicis* powders despite solvent-dependent variation

The acid (0.01 ± 0.00 to 0.11 ± 0.01 mg·KOH/g powder), peroxide (0.62 ± 0.22 to 3.97 ± 0.17 meq·O_2/kg powder), anisidine (0.39 ± 0.06 to 3.56 ± 0.88), and TBARS (0.12 ± 0.01 to 0.32 ± 0.02 MDA/kg powder) indices of the powders generally comply with international standards, particularly those of the Codex Alimentarius. These low values can be attributed to the low lipid contents, which reduce susceptibility to oxidation [15].

Powders obtained from *R. phoenicis* larvae defatted with hexane and hexane:isopropanol exhibited the highest PVs, at 3.97 ± 0.17 and 1.74 ± 0.31 meq·O_2/kg powder, respectively, compared to those defatted

with ethanol and by cooking-pressing. However, powder defatted using hexane (HDP) showed significantly higher anisidine index and TBARS value than ethanol (EDP) and cold-pressed defatted powder (CPDP).

PV measures primary oxidation products (hydroperoxides), indicative of early-stage lipid oxidation. p-AnV and TBARS measure secondary oxidation products (reactive aldehydes and MDA, respectively) formed by the decomposition of hydroperoxides, indicative of more advanced oxidation. The apparent discrepancy between high PV in hexane:isopropanol mixture (HIPDP) (3.97 meq·O_2/kg) and high p-AnV/TBARS in hexane (HDP) reflects different positions along the oxidative cascade: hexane:isopropanol mixture (HIPDP) accumulated primary hydroperoxides that had not yet decomposed into secondary products, while hexane (HDP) showed more advanced oxidation with greater production of carbonyl compounds and MDA derivatives. Given that *R. phoenicis* larvae contain tocopherols acting as natural antioxidants [13, 14], this difference could be explained by variations in tocopherol content among the different types of powders. In powders obtained by defatting with the hexane:isopropanol (HIP) mixture, these antioxidants are less removed, thereby delaying the decomposition of hydroperoxides. In contrast, in powders produced after hexane defatting, lipophilic antioxidants are likely more extensively extracted, which promotes the formation of secondary oxidation products. Despite these differences, all the observed values remain low and consistent with quality standards, indicating that these powders do not present any particular risk for human consumption, in terms of chemical stability.

Cooking-pressing enhances oxidative stability of *R. phoenicis* oils compared to solvent extraction

The AV of the oils extracted from *R. phoenicis* larvae using different methods ranged from 0.00 ± 0.00 to 0.05 ± 0.01 mg·KOH/g lipid. These values are lower than those previously obtained (0.6 mg·KOH/g lipid) for *R. phoenicis* larva powder defatted by cooking-pressing [15]. Generally, the AVs obtained are significantly below the threshold of 4 mg·KOH/g lipid recommended by the Codex Alimentarius [48, 49]. This result indicates that the lipids from *R. phoenicis* larvae are highly stable against hydrolysis. The stability of these lipids to hydrolysis is a key factor in their quality and shelf life [16].

The highest PV were observed for oils extracted with hexane (17.30 ± 0.99 meq·O_2/kg lipid) and hexane:isopropanol (14.40 ± 1.08 meq·O_2/kg), while the lowest PVs were obtained for oils extracted with ethanol (1.54 ± 0.75 meq·O_2/kg) and by cooking-pressing (5.05 ± 0.80 meq·O_2/kg lipid). These values follow similar trends to those obtained from *H. illucens* larvae defatted with hexane (11.7 meq·O_2/kg lipid) and by mechanical pressing (2.9 meq·O_2/kg lipid), confirming that defatting by cooking-pressing helps limit oxidation [50]. Although quality standards for insects have not yet been established, it should be noted that the values obtained for oil extracted with hexane and hexane:isopropanol exceed the limit recommended by the Codex Alimentarius standard (15 meq·O_2/kg lipid), whereas those obtained by ethanol extraction and cooking-pressing are below the Codex Alimentarius recommended limit (10 meq·O_2/kg lipid) [48]. These results indicate that these solvent systems are capable of more completely extracting primary oxidation products. However, a high PV indicates initial oxidation. Extraction methods and the solvents used can significantly influence the PV of extracted oils, as certain solvents may extract oxidized compounds more efficiently or promote oxidation during the process [51].

The p-AnV of the oils varied between 1.07 ± 0.32 for CPO and 11.50 ± 0.56 for ethanol extraction (EO). Generally, these values are below 20, the maximum limit recommended for oils [52]. Although ethanol extraction (EO) showed a high p-AnV (11.50 ± 0.56), indicating significant secondary oxidation, hexane extraction (HO) (1.34 ± 0.12) and CPO (1.07 ± 0.32) presented lower values. Despite its less favorable oxidative profile and environmental concerns, hexane was included as a practical reference because it remains the industrial gold standard for lipid extraction, providing a benchmark for maximum theoretical lipid recovery against which alternative green solvents and mechanical methods must be evaluated [29].

These results highlight a trade-off between extraction efficiency and the quality of oils from *R. phoenicis* larvae. While non-polar solvents maximize lipid removal, they may also increase susceptibility to oxidation, as evidenced by higher PVs. In contrast, milder methods such as ethanol extraction and mechanical pressing, despite their lower efficiency, may better preserve the oxidative stability of the extracted lipids.

Defatting of *R. phoenicis* larvae by cooking-pressing yields powders with significant emulsifying capacity, as well as good water and oil absorption capacities

The techno-functional properties of powders from larvae of *R. phoenicis* varied considerably depending on the defatting method. The WAC of the powders ranged from 1.10 ± 0.02 mL/g (ethanol, EDP) to 1.49 ± 0.05 mL/g (hexane:isopropanol mixture, HIPDP). These WAC values are lower than those reported for *G. bimaculatus*, where ethanol-defatted powder showed a higher WAC than hexane-defatted powders [25]. The higher WAC observed in hexane:isopropanol mixture (HIPDP) and cold-pressed defatted powder (CPDP) could be explained by structural modifications and greater exposure of hydrophilic protein groups [23]. Indeed, defatting can increase WAC by releasing water-binding sites that were previously masked by lipids [25]. The low value obtained with ethanol-defatted powder (EDP) primarily suggests protein denaturation. As a polar solvent, ethanol can induce significant structural changes, leading to protein aggregation and a reduction in their surface area available for interaction with water, a phenomenon observed in many insect powders. This low value may also be due to a reduction in hydrophilic constituents in the larvae caused by ethanol during the defatting process.

For OAC, the values ranged from 1.48 ± 0.04 mL/g (hexane, HDP) to 3.11 ± 0.09 mL/g (ethanol, EDP). Ethanol (EDP) showed the highest OAC, 3.11 ± 0.09 mL/g, which is higher than the value of 2.31 ± 0.09 g/g reported for ethanol-defatted powders from *G. bimaculatus* larvae [25]. In contrast, hexane (HDP) and hexane:isopropanol mixture (HIPDP) exhibited the lowest values, suggesting a reduction in hydrophobic constituents in the powders during defatting. The high OAC observed in ethanol (EDP) could be attributed to the exposure of hydrophobic protein groups following ethanol-induced denaturation and their subsequent interaction with oil [25]. Indeed, ethanol can modify the tertiary structure of proteins, exposing their hydrophobic core and thereby increasing their affinity for lipids. It has also been demonstrated that certain organic solvents such as hexane and ethanol increase protein surface hydrophobicity compared to mechanical pressing [22].

The EC ranged from 40.00 ± 8.66% (ethanol, EDP) to 66.70 ± 2.89% (cold-pressed defatted powder, CPDP). These emulsifying capacities are lower than the values of about 100% reported for defatted powders of *Protaetia brevitarsis*, where the type of defatting solvent did not influence EC [53]. However, in *H. illucens*, a higher value was also observed in powders defatted by cooking-pressing compared with those obtained by solvent extraction [22]. The superior EC value observed for cold-pressed defatted powder (CPDP) can be attributed to the moderate thermal treatment applied during the pre-heating phase (50°C). This mild heating induces a partial unfolding of the protein structure, exposing previously buried hydrophobic amino acid residues. This increased surface hydrophobicity enhances the proteins' ability to rapidly adsorb at the oil-water interface and form a stable viscoelastic film around lipid droplets, thereby improving emulsifying properties [22, 23].

This suggests that proteins may remain more functionally suitable after cooking-pressing than after extraction with organic solvents. In addition, the possible presence of residual lipoprotein complexes in cold-pressed defatted powder (CPDP) could enhance the formation of stable interfacial films. For hexane (HDP) and hexane:isopropanol mixture (HIPDP), the relatively high emulsifying capacities may also be attributed to their high protein content (around 50%). High protein levels are often associated with improved emulsifying properties, particularly when proteins exhibit strong hydrophobicity, enabling them to adsorb at the water–air interface and reduce interfacial tension [54]. The lower EC of the ethanol (EDP) powder (40.00%) highlights the detrimental effect of ethanol-induced denaturation on surface properties, reducing the ability of proteins to unfold and stabilize oil droplets.

This comparison of techno-functional properties among powders obtained from different defatting methods nevertheless presents certain limitations. Although all powders were sieved through a 0.64 mm mesh, the distribution of particle sizes below this threshold was not characterised. Since particle size affects the surface area available for hydration and lipid interaction, future studies should include laser diffraction analysis to assess potential PSD-related confounding effects on techno-functional properties, as previously recommended for insect ingredient research [20].

Conclusion

This study demonstrates that the defatting method significantly influences the nutritional composition, physicochemical characteristics, and techno-functional properties of powders and oils derived from *R. phoenicis* larvae. Hexane extraction and the hexane:isopropanol mixture were the most effective in increasing protein content, but these methods may also enhance oxidative susceptibility. In contrast, mechanical processing (cooking-pressing) and ethanol extraction, although less efficient in lipid removal, better preserve oxidative stability while providing advantageous techno-functional properties, such as improved EC and high OAC.

Therefore, the selection of a defatting method should be guided by the intended application. Ethanol-defatted powders, characterized by high OAC, are particularly suitable for baking and formulated meat products where fat retention is essential. Conversely, powders obtained by cooking-pressing or hexane extraction, which exhibit superior emulsifying properties and high protein content, are well suited for protein beverages, soups, and emulsion-based formulations. For protein fortification and nutritional supplements, hexane-based methods remain the most appropriate due to their high protein yield.

However, the greater oxidative susceptibility of solvent-defatted powders highlights the need for stabilization strategies, including the use of antioxidants (e.g., mixed tocopherols, rosemary extract) and protective packaging (vacuum or modified atmosphere). Overall, these findings underscore the potential of reduced-fat *R. phoenicis* larval powders as sustainable and functional food ingredients, contributing to the development of innovative products and supporting global food security.

Abbreviations

AV: acid value

CPDP: cook-press defatted powder

CPO: cook-pressed extracted oil

EC: emulsifying capacity

EDP: ethanol-defatted derived powder

EO: ethanol-extracted oil

HDP: hexane-defatted powder

HIPDP: hexane:isopropanol defatted powder

HIPO: hexane:isopropanol extracted oil

HO: hexane-extracted oil

ISO: International Standard Organization

MDA: malondialdehyde

OAC: oil absorption capacity

p-AnV: p-anisidine value

PV: peroxide value

TBARS: thiobarbituric acid reactive substances

TCA: trichloroacetic acid

WAC: water absorption capacity

Declarations

Author contributions

LKG: Investigation, Writing—original draft, Formal analysis, Investigation, Writing—review & editing. ARFM: Conceptualization, Data curation, Methodology, Project administration, Validation, Writing—original

draft, Writing—review & editing. NPN: Validation, Writing—review & editing. ADM: Validation, Writing—review & editing. GSKM: Investigation, Writing—review & editing. LPKF: Validation, Writing—review & editing. FFDD: Validation, Writing—review & editing. GK: Resources, Supervision, Writing—review & editing. IG: Resources, Supervision, Writing—review & editing. All authors read and approved the submitted version.

Conflicts of interest

The authors declare that they have no conflicts of interest.

Ethical approval

Not applicable.

Consent to participate

Not applicable.

Consent to publication

Not applicable.

Availability of data and materials

The raw data supporting the conclusions of this manuscript will be made available by the authors, without undue reservation, to any qualified researcher

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References

1. FAO, IFAD, UNICEF, WFP, WHO. The State of Food Security and Nutrition in the World 2025. Rome: FAO, IFAD, UNICEF, WFP, WHO; 2025. [DOI]
2. FAO, IFAD, UNICEF, WFP, WHO. The State of Food Security and Nutrition in the World 2024. Rome: FAO, IFAD, UNICEF, WFP, WHO; 2024. [DOI]
3. Henchion M, Hayes M, Mullen AM, Fenelon M, Tiwari B. Future Protein Supply and Demand: Strategies and Factors Influencing a Sustainable Equilibrium. Foods. 2017;6:53. [DOI] [PubMed] [PMC]
4. Van Huis A, Van Itterbeeck J, Klunder H, Mertens E, Halloran A, Muir G, et al. Edible insects: Future prospects for food and feed security. Rome (Italy): Food and Agriculture Organization of the United Nations (FAO); 2013.
5. Oonincx DG, de Boer IJ. Environmental Impact of the Production of Mealworms as a Protein Source for Humans – A Life Cycle Assessment. PLoS ONE. 2012;7:e51145. [DOI] [PubMed] [PMC]
6. Miglietta P, De Leo F, Ruberti M, Massari S. Mealworms for Food: A Water Footprint Perspective. Water. 2015;7:6190–203. [DOI]
7. Ambele F, Chia S, Nsobinenyui D, Akutse K, Ngantu N, Akumeyam A, et al. Edible insects as a sustainable solution to food insecurity in conflict-ridden regions of Cameroon. J Insects Food Feed. 2025;11:2267–87. [DOI]

8. Dounias E. L'exploitation méconnue d'une ressource connue : la collecte des larves comestibles de charançons dans les palmiers raphias au sud Cameroun. In: Motte-Florac E, Thomas JMC, editors. Les insectes dans la tradition orale. Peeters-SELAF; 2003. pp. 205–26.
9. Siddiqui S, Aidoo O, Ghisletta M, Osei-Owusu J, Saraswati Y, Bhardwaj K, et al. African edible insects as human food – a comprehensive review. J Insects Food Feed. 2023;10:51–78. [DOI]
10. Womeni H, Tiencheu B, Linder M, Nabayo E, Tenyang N, Mbiapo F, et al. Nutritional value and effect of cooking, drying and storage process on some functional properties of Rhynchophorus phoenicis. Int J Life Sci Pharma Res. 2012;2:203–19.
11. Ayemele A, Muafor F, Levang P. Indigenous management of palm weevil grubs (Rhynchophorus phoenicis) for rural livelihoods in Cameroon. J Insects Food Feed. 2017;3:43–50. [DOI]
12. Tamesse J, Kekeunou S, Tchatchouang L, Ndegue O, Aissatou L, Tombouck D, et al. Insects as food, traditional medicine and cultural rites in the west and south regions of Cameroon. J Insects Food Feed. 2016;2:153–60. [DOI]
13. Fogang Mba AR, Kansci G, Viau M, Hafnaoui N, Meynier A, Demmano G, et al. Lipid and amino acid profiles support the potential of Rhynchophorus phoenicis larvae for human nutrition. J Food Compos Anal. 2017;60:64–73. [DOI]
14. Fogang Mba AR, Kansci G, Viau M, Ribourg L, Fogoh Muafor J, Hafnaoui N, et al. Growing conditions and morphotypes of African palm weevil (*Rhynchophorus phoenicis*) larvae influence their lipophilic nutrient but not their amino acid compositions. J Food Compos Anal. 2018;69:87–97. [DOI]
15. Motou W, Mba A, Mawamba A, Ntieche M, Mfombam A, Koule J, et al. Storage Stability of *Rhynchophorus phoenicis* Larvae Powder: Changes in Nutritional, Physicochemical, Water and Oil Absorption Properties Under Packaging Materials. J Food Nutr Sci. 2026;14:68–81. [DOI]
16. Tiencheu B, Womeni HM, Linder M, Mbiapo FT, Villeneuve P, Fanni J, et al. Changes of lipids in insect (*Rhynchophorus phoenicis*) during cooking and storage. Eur J Lipid Sci Technol. 2012;115:186–95. [DOI]
17. Fogang Mba AR, Ngono Eyenga SNN, Mbogning Feudjio W, Geairon A, Kermarrec A, Rabesona H, et al. Quality and Stability Evaluation of Rhynchophorus Phoenicis Larvae Powder Under Thermal and Defatting Treatments: Biochemical and Fluorescence Spectroscopy Analysis. Food Biophys. 2026;21: e21. [DOI]
18. Saini RK, Prasad P, Shang X, Keum YS. Advances in Lipid Extraction Methods—A Review. Int J Mol Sci. 2021;22:13643. [DOI] [PubMed] [PMC]
19. Tzompa-Sosa DA, Yi L, van Valenberg HJ, van Boekel MA, Lakemond CM. Insect lipid profile: aqueous versus organic solvent-based extraction methods. Food Res Int. 2014;62:1087–94. [DOI]
20. Laurent S, Jury V, de Lamballerie M, Fayolle F. Effect of two defatting processes on the physicochemical and flow properties of *Hermetia illucens* and *Tenebrio molitor* larvae powders. J Food Process Preserv. 2022;46:e46. [DOI]
21. Laroche M, Perreault V, Marciniak A, Gravel A, Chamberland J, Doyen A. Comparison of Conventional and Sustainable Lipid Extraction Methods for the Production of Oil and Protein Isolate from Edible Insect Meal. Foods. 2019;8:572. [DOI] [PubMed] [PMC]
22. Kim TK, Lee JH, Yong HI, Kang MC, Cha JY, Chun JY, et al. Effects of Defatting Methods on the Physicochemical Properties of Proteins Extracted from Hermetia illucens Larvae. Foods. 2022;11: 1400. [DOI] [PubMed] [PMC]
23. Marasca NS, de Sousa Araújo AC, da Silva Noda K, de Farias BS, Brizio APDR, Fernandes SS, et al. Effect of Defatting Method on the Nutritional, Functional, and Bioactive Properties of Black Soldier Fly (Hermetia illucens) Larvae. Insects. 2025;16:844. [DOI] [PubMed] [PMC]
24. Rose A, Chiu Y, Showman C, Ku KM, Jaczynski J, Matak K. Characterization of protein concentrates obtained by defatting cricket, locust, and silkworm powders using one-step organic solvent extraction. LWT. 2023;182:114876. [DOI]

25. Jeong MS, Lee SD, Cho SJ. Effect of Three Defatting Solvents on the Techno-Functional Properties of an Edible Insect (Gryllus bimaculatus) Protein Concentrate. Molecules. 2021;26:5307. [DOI] [PubMed] [PMC]
26. Carré P, Bothe S, Borah CD, Piofczyk T, Hadjiali S. Solvent solutions: comparing extraction methods for edible oils and proteins in a changing regulatory landscape. Part 5: Impacts on the oil quality. OCL. 2025;32:6. [DOI]
27. L'hocine L, Boye JI, Arcand Y. Composition and Functional Properties of Soy Protein Isolates Prepared Using Alternative Defatting and Extraction Procedures. J Food Sci. 2006;71:e71. [DOI]
28. Pellerin G, Doyen A. Effect of thermal and defatting treatments on the composition, protein profile and structure of house cricket (Acheta domesticus) protein extracts. Food Chem. 2024;448:139149. [DOI] [PubMed]
29. Abutaha N, Al-Mekhlafi FA. Green Solvent-Based Extraction of Lipids and Proteins from Tenebrio molitor: A Sustainable Approach and Cytotoxic Activity. Food Sci Anim Resour. 2025;45:807–20. [DOI] [PubMed] [PMC]
30. Zhao X, Vázquez-Gutiérrez JL, Johansson DP, Landberg R, Langton M. Yellow Mealworm Protein for Food Purposes - Extraction and Functional Properties. PLOS ONE. 2016;11:e0147791. [DOI] [PubMed] [PMC]
31. Ngono NNSE, Fogang RAM, Mounjouenpou P, Kansci G. Nutritional, functional properties and estimated shelf-life of defatted Rhynchophorus phoenicis (Fabricius, 1801) larvae flours. Int J Biol Chem Sci. 2024;17:2439–55. [DOI]
32. Iberahim NI, Tan BC. Hexane-isopropanol Extraction and Quality Assessment of Omega-3 Fish Oil from Atlantic Salmon (Salmo Salar). IOP Conf Ser: Mater Sci Eng. 2020;932:012038. [DOI]
33. Hara A, Radin NS. Lipid extraction of tissues with a low-toxicity solvent. Anal Biochem. 1978;90: 420–6. [DOI] [PubMed]
34. AFNORNF. NF V04-401: Viandes, produits à base de viandes et produits de la pêche - Détermination de l'humidité. Paris (France): AFNOR; 2001.
35. AFNORNF. NF V04-407: Viandes, produits à base de viandes et produits de la pêche - Détermination de la teneur en azote total et calcul de la teneur en protéines - Méthode Kjeldahl. Paris (France): AFNOR; 2002.
36. AFNORNF. NF V04-402: Viandes et produits à base de viande - Détermination de la teneur en matière grasse totale. Paris (France): AFNOR; 1967.
37. Atwater WO, Benedict FG. Experiments on the metabolism of matter and energy in the human body, 1898-1900. University of Florida, George A. Smathers Libraries; 1902. [DOI]
38. BSI. BS EN ISO 660: 2020 Animal and vegetable fats and oils. Determination of acid value and acidity. BSI; 2020. [DOI]
39. IDF. International Dairy Federation Standard Methods, Sec. 74A, Square Vergote 41. Brussels (Belgium): IDF; 1991.
40. Draper HH, Hadley M. Malondialdehyde determination as index of lipid Peroxidation. Methods Enzymol. 1990;186:421–31. [DOI] [PubMed]
41. AFNORNF. ISO 6885: 2016: Corps gras d'origines animale et végétale - Détermination de l'indice d'anisidine. Paris (France): AFNOR; 2016.
42. LIN MJY, HUMBERT ES, SOSULSKI FW. CERTAIN FUNCTIONAL PROPERTIES OF SUNFLOWER MEAL PRODUCTS. J Food Sci. 2006;39:368–70. [DOI]
43. Wu H, Wang Q, Ma T, Ren J. Comparative studies on the functional properties of various protein concentrate preparations of peanut protein. Food Res Int. 2009;42:343–8. [DOI]
44. European Commission. Commission implementing regulation (EU) 2022/169 of 8 February 2022 authorising the placing on the market of frozen, dried and powder forms of yellow mealworm (Tenebrio molitor larva) as a novel food under Regulation (EU) 2015/2283 of the European Parliam. European Commission; 2022. pp. 10–6.

45. European Commission. Règlement d'exécution (UE) 2022/188 de la commission du 10 février 2022 autorisant la mise sur le marché de formes congelée, séchée et en poudre d'Acheta domesticus en tant que nouvel aliment en application du règlement (UE) 2015/2283 du Parlement europée. European Commission; 2022. pp. 108–14.
46. European Commission. Règlement d'exécution (UE) 2023/58 de la commission du 5 janvier 2023 autorisant la mise sur le marché des formes congelée, lyophilisée, en pâte et en poudre de larves d'Alphitobius diaperinus (petit ténébrion mat) en tant que nouvel aliment et modifiant . European Commission; 2023. pp. 10–5.
47. European Commission. Commission implementing regulation (EU) 2021/1975 of 12 November 2021 authorising the placing on the market of frozen, dried and powder forms of Locusta migratoria as a novel food under Regulation (EU) 2015/2283 of the European Parliament and of the Counc. European Commission; 2021. pp. 10–6.
48. Hishamuddin E, Sulaiman N, Ahmad Bustamam FK, Yeoh CB. Recent Updates on the Codex Standard for Named Vegetable Oils (CXS 210-1999) in Relation to Palm Oil and Palm Kernel Oil. Palm Oil Dev. 2020;72:34–41.
49. FAO, WHO. CXS-19-1981. Standard for edible fats and oils not covered by individuals standards. FAO, WHO; 2021.
50. Hurtado-Ribeira R, Hernández DM, Villanueva-Bermejo D, García-Risco MR, Hernández MD, Vázquez L, et al. The Interaction of Slaughtering, Drying, and Defatting Methods Differently Affects Oxidative Quality of the Fat from Black Soldier Fly (Hermetia illucens) Larvae. Insects. 2023;14:368. [DOI] [PubMed] [PMC]
51. Mohammad Taghi Gharibzahedi S, Altintas Z. Lesser mealworm (Alphitobius diaperinus L.) larvae oils extracted by pure and binary mixed organic solvents: Physicochemical and antioxidant properties, fatty acid composition, and lipid quality indices. Food Chem. 2023;408:135209. [DOI] [PubMed]
52. GOED. GOED voluntary monograph. GOED; 2022.
53. Kim TK, Yong HI, Kim YB, Jung S, Kim HW, Choi YS. Effects of organic solvent on functional properties of defatted proteins extracted from Protaetia brevitarsis larvae. Food Chem. 2021;336:127679. [DOI] [PubMed]
54. Mishyna M, Martinez JI, Chen J, Benjamin O. Extraction, characterization and functional properties of soluble proteins from edible grasshopper (Schistocerca gregaria) and honey bee (Apis mellifera). Food Res Int. 2019;116:697–706. [DOI] [PubMed]