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Unlocking the potential of insect powders for the development of sustainable and nutritious foods: Nutritional and techno-functional properties

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ABSTRACT

This study presents a systematic, side-by-side comparison of the nutritional composition, techno-functional properties, physicochemical characteristics, and antioxidant activity of powders from three edible insect species: *Tenebrio molitor* (TMP), *Locusta migratoria* (LMP), and *Acheta domesticus* (ADP). While many studies have examined the composition of insect powders, few have integrated both nutritional and functional assessments to inform targeted food formulation. Results showed all insect powders are protein-rich (50.0–65.5 %), with varying fat (14.3–21.5 %) and dietary fiber content (3.3–10.6 %). Amino acid profiles of TMP and ADP met FAO requirements for adults, comparable to conventional protein sources (LMP showed minor deficiencies in lysine and sulphur amino acids), while all samples exhibited beneficial unsaturated fatty acid profiles, with notable α-linolenic acid content in LMP. LMP demonstrated superior mineral content and significantly higher antioxidant activity (significantly higher FRAP and FIC values), followed by ADP and TMP. Importantly, all powders exhibited high emulsifying and gelling capacities, with LMP outperforming the others in most functional metrics. These findings underscore the potential of insect powders not only as sustainable protein sources but also as multifunctional ingredients for food product development. The comparative analysis highlights the importance of species-specific selection based on nutritional targets and functional requirements, offering valuable guidance for the formulation of innovative, consumer-acceptable food products.

1. Introduction

During the last decade, the discussion on the use of insects as a source of alternative proteins has aroused the interest of all sectors of the population. Reasons such as the rising in the protein demand due to the growing population (Kaneda and Bietsch, 2020), the sustainability of their production (they require less use of land and water and generate fewer greenhouse emissions compared to conventional livestock) (Brena-Melendez et al., 2024; FAO, 2021; Gahukar, 2016; Vale-Hagan et al., 2023) and their high nutritional value (Juárez-Barrientos et al., 2024; Veldkamp et al., 2012), have been argued to be determinant in the growing interest aroused at all levels. This new interest is more evident specially in countries where their consumption is not usual. This is the case of the European Union (EU) where edible insects have been recently regulated as novel foods by the European Food Safety Authority (EFSA), requiring pre-market authorization (Regulation EU 2015/2283). Currently, the EU has authorized the human consumption of four types of insects in different forms, such as frozen, dried, powdered or paste: the larvae of *Tenebrio molitor* (mealworm), the migratory locust (*Locusta migratoria*), the house cricket (*Acheta domesticus*) and the larvae of *Alphitobius diaperinus* (dung beetle) (Regulation EU 2023/58). Although they are already consumed in many parts of the world, in the others

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(Western countries), entomophagy is still considered a repugnant practice (with negative traits such as neophobia and disgust) (Tan et al., 2015). However, these negative consumers' attitudes and perception can be changed when insects are used in a form in which they could not be directly perceived by the consumers (such as powders or extracts), together with an effective communication of information (highlighting their sustainability and environmental friendliness). These insect powders can be used not only to enrich food products nutritionally but also to replace traditional protein or fat sources, enabling the development of hybrid or reformulated foods (Grasso and Goksen, 2023). Critically, the success of such formulations depends not only on the nutritional quality of insect powders but also on their functional behavior within food systems (Aguilera, 2025; Townsend et al., 2023). These new ingredients must be evaluated for their impact on food matrices—whether stabilizing emulsions, forming gels, or affecting texture, taste (Mihafu et al., 2020; Świąder and Marczewska, 2021), and nutrient bioavailability (Fardet and Rock, 2022; Miao and Hamaker, 2021; Samtiya et al., 2021). While previous studies have explored compositional aspects of insect powders, few have conducted comprehensive, side-by-side evaluations that integrate both nutritional profiling and techno-functional characterization across *Multiple species*. Such integrative data are crucial for food scientists and product developers to make informed choices about ingredient selection, depending on whether the goal is to improve protein quality, optimize texture in bakery goods, or enhance emulsification in beverages.

The aim of this study is to provide a detailed characterization of *T. molitor,* L. *migratoria*, and *A. domesticus* powders, focusing on their proximate composition, amino acid, fatty acid, and mineral profiles, as well as their antioxidant properties and techno-functional behavior. This knowledge will support targeted incorporation of insect powders into diverse food applications, based on specific nutritional and functional goals**.**

2. Materials and methods

2.1. Materials

Insects (*T. molitor* larvae, *A. domesticus* and L. *migratoria*) were purchased from Insectum (Valencia, Spain), an authorized company to sell insects for human consumption. *T. molitor* larvae and *A. domesticus* were provided directly as powders, indicating that are dry insects finally ground into powders. L. *migra*toria was not offered by the company in the form of powder, only the dried insect, so the grinding process was done in our lab (IPOA laboratory, CIAGRO-UMH, Orihuela, Valencia, Spain), using a rotor mill ZM 200 (Retsch GmbH, Hann, Germany). Fig. 1 shows the appearance of the three insect powders studied. All samples (powders) were vacuum packed in hermetically sealed aluminum bags to protect them from light and moisture.

2.2. Proximate composition of insect powders

The moisture (oven air-drying method), ash (muffle furnace), protein (Kjeldahl method), total dietary fiber (enzymatic-gravimetric method) and fat content (Soxhlet extraction) were determined following official methods (AOAC, 2010). These measures were made in triplicate per batch of each insect powder ($n = 3$).

2.3. Fatty acid profile of insect powders

To analyze the fatty acid composition, total fat extraction was initially carried out following the AOAC (2010) methodology. Afterwards, the fatty acids were converted into their methyl esters (FAMEs), which were separated and quantified using an HP 6890 gas chromatograph (GC) from Agilent Technologies (Santa Clara, CA, USA). The working parameters were the same as described by (Botella-Martínez et al., 2020). Identification of individual fatty acids was achieved by comparing retention times with standards of pure compounds (Supelco 37 Component FAME Mix, Bellefonte, USA). Peak integration was performed using the ChemStation software (Agilent Technologies), and the results were expressed as grams of fatty acid per 100 g of total fat. Each sample value was calculated as the average of three replicates.

Based on the lipid composition of the different insect powders, several nutritional quality parameters were determined, including the ratios of saturated to unsaturated fatty acids (SFA/UFA), omega-6 to omega-3 fatty acids (n-6/n-3), as well as the atherogenic index (AI), thrombogenic index (TI), and the hypocholesterolaemic to hypercholesterolaemic ratio (h/H), following the criteria described by Chen & Liu (2020).

2.4. Amino acid profile of insect powders

Amino acids were subjected to acid hydrolysis and pre-column derivatisation with 6–aminoquinolyl-N-hydroxysuccinimidyl carbamate (AQC), then separated by HPLC and analysed by fluorescence detection, following the method described by Domínguez et al. (2015). Briefly, the protein of the sample was hydrolysed with hydrochloric acid (6 N) at 110 °C for 24 h. After hydrolysis, the samples were neutralised with sodium hydroxide (8 M), adjusted to volume and filtered at 0.22 µm. The derivatisation step was then carried out according to the manufacturer's instructions (Waters, AccQTag Ultra Derivatization Kit). Separation and quantification of amino acids were carried out using high-performance liquid chromatography (Acquity Arc, de Waters,

Fig. 1. Powders from edible insects: A. domesticus (ADP), T. molitor (TMP) and L. migratoria (LMP).

Milford, MA, USA) equipped with a scanning fluorescence detector (model 2475, Waters, Milford, MA, USA). For the separation of amino acids, a Waters AccQ-Tag column (3.9 × 150 mm, with a particle size of 3 μm) was used. Data acquisition, equipment control, and data analysis were carried out using the HPLC software (Empower 3TM; Waters, Milford, MA, USA). The amino acids were identified by comparing their retention time with the authenticated standards. The results were expressed as mg/100 g of sample. It should be noted that, in this study, the hydrolysis performed in the amino acids' experimental protocol is not specific for determining the presence and quantification of tryptophan.

2.5. Mineral profile of insect powders

Mineral profile of insect powders (dried samples) was determined in triplicate using a Shimadzu MS-2030 inductively coupled plasma mass spectrometry (ICP-MS) (Shimadzu, Kyoto, Japan). Samples (lyophilized) were previously digested with nitric acid and hydrogen peroxide in a microwave. Standard compounds were diluted and used to calibrate the ICP-MS. The ICP-MS was operated under the following conditions: carrier gas 0.70 L/min; plasma gas 9.0 L/min; auxiliary gas 1.10 L/min; radio frequency 1.2 kW, power filter 7.0 V. The samples of insect powders were diluted at 1:5 before their measure at ICP-MS. Finally, values per sample were obtained by averaging three readings.

2.6. Physicochemical properties of insect powders

Water activity (aw) was determined at 25 °C using a NOVASINA TH200 electric hygrometer (Novasina; Axair Ltd., Pfaeffikon, Switzerland). The pH was measured in a water solution (solid: liquid ratio 1:20 g/mL) after 20 min of magnetic stirring with a pH meter (Model 507, Crison Instruments SA, Barcelona, Spain). Color was evaluated with a Minolta CM-700 spectrophotocolorimeter (Minolta Camera Co., Osaka, Japan) using the Observer 10°, illuminant D65, 11 mm instrument aperture for illumination and 8 mm for measurement. The CIELab color space was selected to obtain the color coordinates: lightness (L*), redness (a*) and yellowness (b*), from which chroma (C*) and hue (H*) were calculated. The reflectance spectrum between 360 and 740 nm (at every 10 nm) were also obtained.

2.7. Techno-functional properties of insect powders

Water holding capacity (WHC) and oil holding capacity (OHC) were measured following the modified centrifugation methods reported by Robertson et al. (2000). Results are expressed as the weight of water or oil held by 1 g of the corresponding powder sample. Swelling capacity (SWC) was assessed following the method described by Gómez-Ordóñez et al. (2010). The volume occupied by the hydrated powder was measured and the results expressed as mL/ g of the corresponding powder sample. Emulsifying capacity (EA) and emulsion stability (ES) were evaluated following the methodology described by López-Marcos et al. (2015). The EA was calculated as the ratio of the depth of the emulsified layer (after the addition of water and sunflower oil for the emulsification procedure and then centrifuged at 1500 rpm, 5 min) to the depth of the total volume (as a percentage). For determining ES, the emulsion formed was further heated (80 °C in a water bath for 30 min) and then cooled down to room temperature, followed by centrifugation under the above same conditions. The ES was calculated in the same way as EA and expressed as percentage of the unheated sample. The gelling capacity (GC) was calculated following the methodology described by Alfaro-Díaz et al. (2021). The samples were mixed with water and the solutions were heated in a water bath at 80 °C for 1 h and cooled to 4 °C for 1 h. The volume of the gel layer was measured relative to the total volume of the solution.

2.8. Antioxidant activity of insect powders

2.8.1. Preparation of extracts

Two grams of each insect's powder were mixed with 20 mL of methanol-water (80:20; v/v). The samples were homogenised individually in Ultraturrax for 2 min at 20,000 rpm with ice bath to avoid overheating and then sonicated in a ultrasonic bath during 12 min at room temperature. Subsequently, the samples were centrifuged at 7000 g during10 min at 4 °C. The supernatant was recovered and the pellet was subjected to another extraction cycle replacing methanol:water by acetone:water (70:30; v/v). The supernatant obtained from the second extraction cycle was mixed with the first one and brought to dryness with a rotary evaporator. Subsequently, they were filtered (0.45 μm nylon filters) and stored at −20 °C until further use. Extraction was carried out in triplicate for each insect powder.

2.8.2. Determination of the in vitro antioxidant activity

2.8.2.1. Antioxidant activity using the 2,2′- diphenyl-1-picrylhydrazyl radical (DPPH) method. The determination was carried out according to the method described by Brand-Williams et al. (1995) with modifications. In brief, DPPH solution (0.06 mM, 2 mL) were mixed with the extracts of insect powders (200 μL). After incubation at room temperature for 30 min in darkness, the absorbance was measured at 517 nm in a T85+ spectrophotometer (PG instruments, Alma Park, Wibtoft Leicestershire, UK). The results were measured by triplicated and expressed as mg Trolox equivalents (TE) / g sample.

2.8.2.2. Antioxidant activity by ferric ion reduction (FRAP). The FRAP method was performed according to the method described by Oyaizu (1986) with modifications. Samples (1000 μL) were mixed with phosphate buffer (0.2 M and pH 6.6; 2.5 mL) and potassium ferricyanide (1 %, 2.5 mL), and incubated in a bath at 50 °C for 20 min. After that, 2.5 mL of 10 % CCl_3COOH were added and shaken for 2 min. Then, 0.1 % iron trichloride was added and the absorbance of the samples was measured at 700 nm in a T85+ spectrophotometer (PG instruments, Alma Park, Wibtoft Leicestershire, UK). The results were measured by triplicated and expressed as mg Trolox equivalents (TE)/g sample.

2.8.2.3. Antioxidant activity by ferrous ion chelation (FIC). This analysis was carried out according to the method described by Mahdavi et al. (2017), with modifications. Briefly, 1000 μL of the extracts of insect' powders were mixed with 0.1 mL of 2 mM $FeSO_4 \cdot 4H_2O$ and 3.7 mL of methanol. After that, 200 μL of ferrozin (5 mM) was included. The absorbance was measured at 562 nm in a T85+ spectrophotometer (PG instruments, Alma Park, Wibtoft Leicestershire, UK). The results were measured by triplicated and expressed as mg EDTA/g sample.

2.9. Statistical analysis

Results are expressed as the mean ± standard deviations of three independent samples. The homogeneity of variances ($P > 0.05$) was assessed by the Levene's test. Differences between insect powders were tested using one-way ANOVA. When a significant effect was found by ANOVA, the Tukey's HSD post-hoc test with a 95 % confidence level was applied. As a measure to the effect sizes, the parameter η^2 was also calculated to assess practical relevance. Principal Component Analysis (PCA) was performed as a multivariate statistical method to reduce data dimensionality and explore the relationships among the chemical, physicochemical, techno-functional and antioxidant variables of the different insect powders. A data matrix was constructed using the mean values of the evaluated variables. A biplot representation was generated to simultaneously visualize the spatial distribution of the samples and the contribution of the original variables to each principal component. The experimental data were analyzed using the software SPSS for windows (IBM SPSS Statistics version 26).

3. Results and discussions

3.1. Proximate composition

The proximate composition of the evaluated samples is shown in Table 1. All the insect powders showed proteins as the first constituent and fats as the second one. Protein content ranged from 50.0 % to 65.5 %, with LMP having the highest content and TMP the lowest ($P < 0.05$). However, fat content showed the opposite behavior showing LMP the lowest values and TMP the highest ($P < 0.05$). The dietary fiber was also an important component ranging from 3.3 % (TMP) to 10.6 % (LMP) ($P < 0.05$). The moisture values of all insect powders were lower than 6 %, showing ADP the lowest values ($P < 0.05$).

Regarding protein content (Table 1), the values obtained are into the range of protein values reported for insects-derived flours from the same species, although it is true that this range is quite wide (46.5 % - 75.6 %) (Brena-Melendez et al., 2024; Juárez-Barrientos et al., 2024; Zielińska, 2022). This variation in protein content within the same species could be attributed to factors such as feed type, sex, climate and geographical location, among others (Brena-Melendez et al., 2024; Juárez-Barrientos et al., 2024; Vanqa et al., 2022). However, this variability in reported protein values has also been related to differences in the method applied, specifically in the kp factor used in the Kheldahl method to convert nitrogen content into protein content. Conventionally, the kp factor used for food is 6.25, based on an average of 16 % nitrogen content in proteins (Mariotti et al., 2008). However, several authors have argued that this kp factor should be reduced to 5.6 in insects due to their richness in chitin (a nitrogenous dietary fiber) whose nitrogen content could be overestimating the protein content (Janssen et al., 2017; Ritvanen et al., 2020). On the other hand, other authors reported that this chitin derived nitrogen might be a minor fraction of the total nitrogen content in several insect species, recommending the use of 6.25 as kp factor in order to obtain a more accurate protein content estimation than 5.6 (Brena-Melendez et al., 2024) and also to standardize the method making it easier to compare data. However, the use of 5.6 as kp factor is recommending in the case of insect protein and fiber isolates (Boulos et al., 2020).

As shown in Table 1, there is a large variation in fat content depending on the insect species: the powder from L. *migratoria* (LMP) had around 1.5 times less fat than *A. domesticus* (ADP) and two times less fat than *T. molitor* (TMP). Nevertheless, the values reported for all insect powders are into the range previously reported by several authors (Brena-Melendez et al., 2024; Lucas-González et al., 2019; Oonincx and van der Poel, 2011). It is important to highlight the inverse relationship between fat and DF content: Insect powders with the highest fat content (TMP) showed the lowest DF content and vice versa ($P < 0.05$). These results could be related to the fact that the fat content in larvae is higher than in adults (Kouřimská and Adámková, 2016), and also that the main source of DF in insects is chitin, which is mainly found in the exoskeleton. The exoskeleton is harder, more resistant and richer in chitin in adults than in larvae (Zhu et al., 2022). In line with this, the DF content varied significantly ($P < 0.05$) between insect powders, showing LMP the highest content and TMP the lowest. It is noticed the high DF content in LMP, which is two time higher than that of ADP and more than three times higher than that of TMP. The DF content reported for edible insects ranged from 2.5 up to 14 % depending on species, development stage, feed, location, etc. (Nachtigall et al., 2025; Zhu et al., 2022). The DF content is one of the most remarkable difference between edible insects and other edible animals, whose meat does not contain DF. So, the enrichment of highly consumed foods (such as meat, bakery and dairy products) with insect powders could contribute to increasing the daily intake of DF in order to achieve the recommended values (Nährstoffzufuhr, 2000).

Finally, the ash content remained into normal values for insect powders, without differences between them ($P > 0.05$). Ash content ranging from 2.2 % to 4.7 % have been reported for house cricket derived flours (Brena-Melendez et al., 2024; Lucas-González et al., 2019), from 2.1 % to 4.8 % for mealworm (Langston et al., 2024) and from 2.1 % to 6.2 % for migratory locust (Oonincx and Van der Poel, 2011). As has been previously discussed, the nutritional variations between insects from the same species could be attributed to several factors such as diet, life stages, location, etc. (Morales-Ramos et al., 2020; Oonincx and van der Poel, 2011).

The η^2 values obtained for all parameters of the proximal composition indicate that the size of the effects is large and that it is therefore important to select the appropriate type of insect powder according to the desired purpose in the food to which it is added.

Table 1
Proximal composition (g/100 g sample) of edible insect powders.

	ADP	TMP	LMP	η^2
Moisture	4.44±0.24^b	5.98±0.25^a	5.78±0.03^a	0.9690
Ash	2.32±0.05^a	2.10±0.05^a	2.23±0.01^a	0.4311
Fat	21.50±2.01^b	30.80±2.95^a	14.33±1.52^c	0.9991
Protein	57.30±3.71^b	50.02±3.92^c	65.52±4.01^a	0.9993
TDF	4.90±0.50^b	3.30±0.21^c	10.61±1.05^a	0.9986

Mean value ± standard error (n = 3). $^{a\text{-}c}$Different superscript letters on the same row indicate significant differences among samples (P < 0.05). TDF: total dietary fiber; ADP: Acheta domesticus powder; TMP: Tenebrio molitor powder; LMP: Locusta migratoria powder.

3.2. Aminoacid profile

Table 2 shows the amino acid profile of the three insect powders analyses. It can be seen that the essential amino acids are found in all of them. However, there were differences ($P < 0.05$) in the amino acid profile depending on the insect species. Also in this case, the η^2 values obtained would indicate large size effect for all the amino acid analyzed. In the three samples, glutamic acid was one of the most abundant amino acid, followed by aspartic acid, alanine and leucine. In ADP, arginine was also highly represented (as one of the 5 most abundant amino acid), as the same as tyrosine in TMP and glycine in LMP. On the other hand, hydroxyproline was only found in LMP, being taurine the least abundant in all of them. The specific amino acid profile varies slightly between different insect species and even within the same species depending on factors like diet and life stage (Nachtigall et al., 2025).

The analysis of the Essential Amino Acid Score (EAAS) could help to understand if the amino acid profile of the insect powders is or not adequate for human nutrition (Fig. 2). This index rates the ability of a food's selected amino acids to meet the human metabolic needs and it is calculated by comparing the amount of each amino acid in the tested food to the amount prescribed by the FAO/WHO standard reference for adults (Oliveira et al., 2024). Although tryptophan (which is also an essential amino acid) could not be determined using the analytical method applied, the calculation of this index for the other amino acids provides relevant information on the quality of the proteins in insect powders. As can be seen in Fig. 2, ADP and TMP completely met the FAO amino acid requirement standards for adult (all EAAS values >100), however, LMP showed sulfur-containing amino acids (methionine + cysteine) and lysine as limiting amino acids (EAAS values <100). Although in the case of ADP and TMP, limiting amino acids were not detected, ADP showed the lowest EAAS for the sulfur-containing amino acids, while in TMP, the lowest EAAS was for lysine. It is important to highlight that ADP and TMP showed higher scores (EAAS, $P < 0.05$) for all evaluated amino acids when compared to LMP. Lysine and sulfur-containing amino acids have been also identified by other authors as limiting amino acids in L. *migratoria* and in some other insect species (Boulos et al., 2020; Köhler et al., 2019; Nachtigall et al., 2025).

In general, it could be said that the amino acid profile of TMP and ADP is comparable to that of other animal-based foods (Tang et al.,

Table 2
Amino acid profile (mg/100 g sample) of edible insect powders.

	ADP	TMP	LMP	η^2
Hydroxyproline	nd	nd	105.96±4.26[a]	0.9992
Aspartic acid	5773.29 ±693.12[a]	4677.14 ±467.84[b]	4425.20 ±368.48[b]	0.7868
Serine	3994.82 ±359.99[a]	3190.89 ±5.76[b]	2702.51 ±294.90[c]	0.9219
Glutamic acid	8690.58 ±1307.07[a]	6323.47 ±760.61[b]	6321.34 ±431.03[b]	0.8194
Glycin	5181.97 ±223.01[a]	3440.84 ±732.29[c]	4268.24 ±546.57[b]	0.9294
Histidine	2342.82 ±98.44[a]	2243.39 ±216.87[a]	1702.92 ±175.03[b]	0.8906
Taurine	536.49±40.88[a]	44.51±1.43[c]	218.16 ±10.80[b]	0.9952
Arginine	6035.72 ±575.77[a]	3452.29 ±477.09[c]	3474.96 ±156.34[b]	0.9578
Threonine	3350.98 ±224.28[a]	2627.83 ±287.17[b]	2374.02 ±165.29[b]	0.9059
Alanine	8915.98 ±1126.48[a]	4351.12 ±531.10c	6555.35 ±772.51[b]	0.9357
Proline	4815.63 ±618.53[a]	3384.94 ±454.38[b]	3607.13 ±448.37[b]	0.8182
Cysteine	579.67 ±18.21[ab]	660.26 ±80.59[a]	523.90 ±21.34[b]	0.7948
Thyrosine	5266.01 ±324.66[a]	4142.41 ±489.43[b]	3042.82 ±231.91[c]	0.9490
Valine	5465.06 ±618.98[a]	3797.63 ±455.52[b]	4047.11 ±422.10[b]	0.8632
Methionine	1010.73 ±96.84[a]	570.93 ±67.62[b]	571.52 ±61.10[b]	0.9474
Lysine	4439.58 ±680.05[a]	3299.95 ±377.14[b]	2981.68 ±202.49[b]	0.8452
Isoleucine	3801.58 ±412.86[a]	2759.63 ±332.57[b]	2756.90 ±228.24[b]	0.8673
Leucine	6386.41 ±746.91[a]	4530.65 ±563.69[b]	4927.630 ±406.68[b]	0.8462
Phenylalanine	2627.39 ±189.66[a]	2427.71 ±280.62[a]	2011.65 ±105.89[b]	0.8246

Mean value ± standard error (n = 3). [a-c]Different superscript letters on the same row indicate significant differences among samples (P < 0.05). nd: not detected; ADP: Acheta domesticus powder; TMP: Tenebrio molitor powder; LMP: Locusta migratoria powder.

2019). However, the digestibility and bioavailability of these proteins and amino acids should be studied to obtain a more accurate assessment of the actual protein quality of the insect powders studied. In the case of LMP, to address its amino acid deficiencies, it can be mixed with other protein sources rich in lysine, such as animal foods, or even soya, or legumes (beans and lentils) (Huamaní-Perales et al., 2024). It must be taken into account that these insect powders will not be consumed on their own, but mixed with other ingredients, forming part of meat, dairy, bakery or even plant-based foods, so these minimal deficiencies can be easily corrected by the other ingredients used.

3.3. *Fatty acid profile*

Table 3 summarizes the fatty acid profile of the three insect powders. As can be seen, in all of them the content of unsaturated fatty acids (UFA) was higher than that of saturated fatty acids (SFA) ($P < 0.05$). LMP showed the highest SFA content, followed by ADP and TMP, in this order ($P < 0.05$). The main (quantitively) SFA in all samples was palmitic acid (C16:0), representing 72 %, 70 % and 66 % of the SFA fraction in LMP, ADP and TMP, respectively. However, while in ADP and LMP the second most abundant SFA was stearic acid (C18:0), in TMP was myristic acid (C14:0). Regarding the UFA fraction, TMP showed the highest values ($P < 0.05$), but only in ADP the PUFA fraction predominates over the MUFA. The main MUFA in all samples was oleic acid (C18:1 *cis*), representing >90 % of the MUFA fraction in all of them. In addition, oleic acid was the main fatty acid (quantitatively) in TMP and LMP. ADP showed the highest PUFA content, followed by TMP and LMP, in this order ($P < 0.05$). The linoleic acid (C18:2) was the predominant PUFA in ADP and TMP, representing >95 % of this fraction. However, the PUFA fraction in LMP was shared (in equal proportions) by linoleic and α-linolenic acid (C18:3), representing both FA >97 % of the PUFA fraction. In general, these lipid profiles are consistent with those reported by other authors for the same species (Jajic et al., 2020; Mohamed, 2015; Paul et al., 2017) even considering that it is dependent on the feed to some degree (Nachtigall et al., 2025). For example, Jajic et al. (2020) reported that oleic acid formed the major lipid component (40.83 %), followed by linoleic acid (29.8 %) and palmitic acid (16.2 %) in dried *T. molitor* larvae. Paul et al. (2017) concluded that oleic and linoleic acids were the predominant fatty component of *T. molitor* larvae and *A. domesticus* lipids. Mohamed (2015) reported that, in L. *migratoria*, the most abundant SFA was the palmitic acid (29.5 %) followed by stearic acid (7.3 %), while oleic acid (38 %) was the major MUFA, and linolenic acid (11.7 %) and α-linolenic acid (14.1 %) the most abundant PUFA. In general, edible insects contain more UFA than SFA and their profile is similar to those of fish and poultry (Ravzanaadii et al., 2012; Yang et al., 2006).

Some index calculated from the lipid profile (as indicators of the nutritional quality of dietary fats) and related to the human lipid metabolism are shown in Table 3. Two of the most used ratios are the

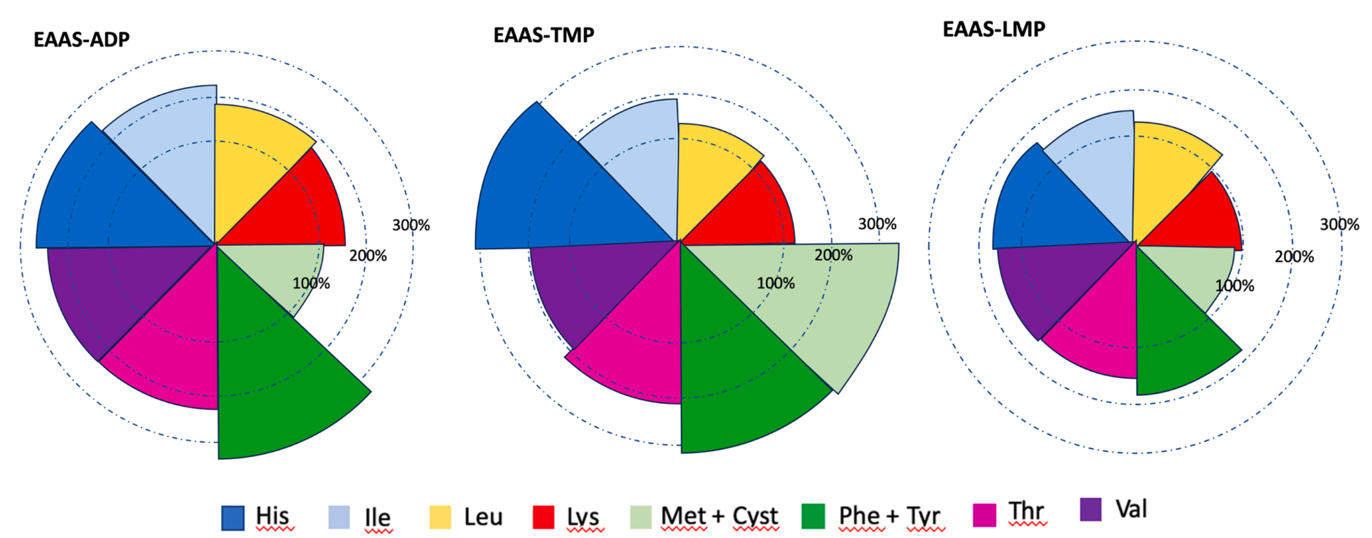

Fig. 2. Essential Amino Acid Score (EAAS; %) of the edible insect powders. n = 3; ADP: A. domesticus powder; TMP: T. molitor powder; L. migratoria powder.

Table 3
Fatty acid profile (g/100 g fat) and nutritional quality indices of edible insect powders.

	ADP	TMP	LMP	η^2
C12:0	0.03 ± 0.01^{c}	0.28 ± 0.01^{a}	0.20 ± 0.03^{b}	0.9732
C14:0	0.48 ± 0.07^{c}	4.47 ± 0.13^{a}	1.96 ± 0.1^{b}	0.9974
C16:0	23.83 ± 0.08^{b}	15.98 ± 0.02^{c}	29.66 ± 0.05^{a}	0.9998
C16:1	0.56 ± 0.03^{b}	1.86 ± 0.03^{a}	1.26 ± 0.01^{a}	0.9984
C17:0	0.26 ± 0.01^{c}	0.16 ± 0.01^{a}	0.24 ± 0.02^{a}	0.2717
C17:1	0.21 ± 0.01^{a}	0.17 ± 0.01^{c}	0.27 ± 0.02^{a}	0.9450
C18:0	9.06 ± 0.08^{a}	3.19 ± 0.03^{b}	9.20 ± 0.03^{a}	0.9996
C18:1 cis	21.09 ± 0.54^{b}	43.26 ± 0.27^{a}	33.02 ± 0.04^{b}	0.9989
C18:2 (n6)	40.22 ± 0.48^{c}	29.49 ± 0.11^{b}	11.15 ± 0.23^{c}	0.9996
C18:3 (n3)	1.31 ± 0.01^{a}	0.66 ± 0.01^{c}	11.02 ± 0.11^{a}	0.9999
C18:3 (n6)	0.24 ± 0.02^{b}	0.13 ± 0.01^{c}	0.18 ± 0.03^{a}	0.9545
C20:0	0.14 ± 0.02^{a}	0.10 ± 0.01^{a}	0.20 ± 0.02^{a}	0.2599
C20:1	0.20 ± 0.01^{b}	0.06 ± 0.01^{b}	0.96 ± 0.17^{a}	0.9573
C24:1	1.75 ± 0.11^{a}	0.09 ± 0.01^{b}	1.12 ± 0.16^{a}	0.9662
SFA	34.01 ± 0.7^{b}	24.20 ± 0.6^{c}	41.49 ± 0.5^{a}	0.9984
UFA	63.86 ± 0.3^{b}	75.95 ± 0.18^{a}	58.45 ± 0.72^{c}	0.9995
MUFA	22.03 ± 0.22^{c}	45.70 ± 0.16^{a}	35.68 ± 0.14^{b}	0.9999
PUFA	41.83 ± 0.15^{a}	30.25 ± 0.15^{b}	22.77 ± 0.12^{c}	0.9998
PUFA/SFA	1.23 ± 0.06^{a}	1.25 ± 0.03^{a}	0.55 ± 0.11^{b}	0.9996
n6/n3 ratio	30.88 ± 0.51^{b}	44.88 ± 0.61^{a}	1.02 ± 0.01^{c}	0.3760
AI	0.11 ± 0.04^{c}	0.43 ± 0.03^{a}	0.20 ± 0.02^{b}	0.9999
TI	0.65 ± 0.08^{b}	1.49 ± 0.06^{a}	0.26 ± 0.05^{c}	0.9999
h/H	78.65 ± 0.1^{a}	9.43 ± 0.02^{c}	10.54 ± 0.02^{b}	0.9999

Mean value ± standard error (n = 3). SFA: saturated fatty acids; UFA: unsaturated fatty acids; MUFA: monounsaturated fatty acids; PUFA: polyunsaturated fatty acids; AI: atherogenic index; TI: thrombogenic index and h/H: hypocholesterolemic/hypercholesterolemic ratio. [a-c]Different superscript letters on the same row indicate significant differences among samples (P < 0.05). ND: not detected; ADP: Acheta domesticus powder; TMP: Tenebrio molitor powder; LMP: Locusta migratoria powder.

PUFA/SFA and the n-6/n-3 index. The PUFA/SFA ratio was greater ($P < 0.05$) in ADP and TMP (without differences between them; $P > 0.05$) than in LMP, which is due to both facts, lower SFA and higher PUFA content in ADP and TMP in comparison with LMP. A PUFA/SFA ratio above 0.4 was advised by Wood et al. (2008), on the premise that a higher ratio yields increasingly positive effects. Regarding this value, all insect powders would meet these requirements. As the typical western diet tends to be high in n6 and low in n3, which potentially increasing the risk of inflammatory and cardiovascular diseases, low n6/n3 ratios are recommended (1–4) (Yang et al., 2023). As can be seen in Table 3, only LMP would meet this recommendation. Other key indicators for forecasting the influence of dietary fats on both nutritional status and cardiometabolic well-being include the atherogenic index (AI), the thrombogenic index (TI), and the hypocholesterolemic/hypercholesterolemic ratio (h/H) (Botella-Martínez et al., 2020; de Souza Paglarini et al., 2019). Notably, the AI and TI have been put forward as effective metrics for preventing coronary heart disease (with lower ratios indicating greater benefits) (Bohrer, 2019). The h/H ratio, conversely, primarily addresses the impact on cholesterol processing (where higher ratios signify more favorable outcomes) (da Silva et al., 2019). In view of that, TMP should show the worst result because exhibiting the lowest h/H ratio and the highest AI and TI indices ($P < 0.05$).

3.4. Mineral profile

The mineral profile of the three insect-based powders is presented in Table 4. ADP showed the highest content in Ca, Na, Mn and K; TMP showed the highest values in Fe, Mg, K and P; LMP showed the highest content in Cu, Fe and Zn ($P < 0.05$). On the contrary, ADP showed the lowest Cu content, TMP the lowest Na content and LMP was the poor source of Ca, Mn and P ($P < 0.05$).

It has been reported that the specific mineral composition can vary significantly between insect species, depending on factors like harvesting season, geographical location, diet, living conditions, growth phase etc. (Lu et al., 2023). And even withing the same insect species, these factors of variation are responsible for wide differences in mineral profiles. So, insect powders offer a diverse range of minerals and can be valuable addition to a balanced diet, potentially addressing mineral deficiencies in humans. For example, TMP and LMP exhibited richer source of Fe than most of common cereals, grains and flours (Koseckova et al., 2022), providing the intake of 100 g of these insects, the 64 % of the Dietary Recommended Values (DRV) per adult male (EFSA, 2019). LMP contained more much Zn than cereals (Ertl and Goessler, 2018). In addition, the intake of 91 g ADP, 56 g TMP or 45 g LMP would reach the DRV for Zn, so, they could greatly promote and adequate dietary supply of Zn (EFSA, 2019). TMP seems to be an excellent source of Mg, because 100 g of TMP can provide the 93 % of the DRV per adult male (EFSA, 2019). On the other hand, the bioaccessibility of these minerals is also a key point to be addressed. Several authors have reported that this bioaccessibility is reduced by some interactions between minerals and proteins, chitin and other phytochemicals (Kosečková et al., 2022). For example, iron in insects is predominantly found as non-heme (as opposed to meat) which reduces its bioaccesibility (Bauserman et al., 2015).

Table 4
Mineral profile (mg/100 g dry weight) of edible insect powders.

	ADP	TMP	LMP	η^2
Calcium	113.38 ± 6.04^{a}	85.60 ± 17.73^{b}	22.54 ± 3.34^{c}	0.7995
Copper	0.86 ± 0.02^{c}	2.56 ± 0.02^{b}	4.43 ± 0.15^{a}	0.9988
Iron	3.14 ± 0.21^{b}	7.13 ± 0.17^{a}	6.97 ± 1.40^{a}	0.9600
Potasium	843.08 ± 24.80^{a}	857.46 ± 10.34^{a}	585.92 ± 27.50^{b}	0.9978
Magnesium	62.69 ± 3.29^{b}	326.82 ± 3.90^{a}	60.25 ± 1.45^{b}	0.9993
Manganese	3.37 ± 0.11^{a}	1.12 ± 0.01^{b}	0.43 ± 0.02^{c}	0.9969
Sodium	274.65 ± 24.55^{a}	84.52 ± 19.90^{c}	139.95 ± 2.04^{b}	0.9998
Phosphorus	677.90 ± 16.99^{b}	969.51 ± 14.43^{a}	415.88 ± 20.46^{c}	0.9976
Zinc	10.24 ± 0.79^{b}	13.49 ± 0.22^{b}	19.32 ± 2.88^{a}	0.9774

Mean value ± standard error (n = 3). [a-c]Different superscript letters on the same row indicate significant differences among samples (P < 0.05). ADP: Acheta domesticus powder; TMP: Tenebrio molitor powder; LMP: Locusta migratoria powder.

3.5. Physicochemical properties

Physicochemical properties of insect powders are shown in Table 5. The water activity of the three insect powders were below 0.57, showing LMP the highest values ($P < 0.05$). These values are into the range of water activity for several flours and are considered to limit microbial growth. However, they could be affected by some enzymatic reactions, such as browning or even oxidant reactions. These problems could be avoided selecting an adequate packaging (vacuum and light protection). In addition, the three insect powders showed pH values ranging from 5.7 to 6.9 (with significant differences between all of them, $P < 0.05$) which is into the range of pH reported for several insect-based flours

Table 5
Physico-chemical and color properties (L*: lightness; a*: redness; b*: yellowness; C*: chroma; H*: hue color) of edible insect powders.

	ADP	TMP	LMP	η^2
pH	6.61 ± 0.03^{b}	6.86 ± 0.01^{a}	5.69 ± 0.03^{c}	0.9981
a_w	0.401 ± 0.01^{c}	0.442 ± 0.03^{b}	0.563 ± 0.01^{a}	0.9954
L*	50.29 ± 0.97^{a}	37.78 ± 1.4^{b}	34.24 ± 1.85^{c}	0.9598
a*	4.26 ± 0.08^{b}	6.08 ± 0.19^{a}	5.94 ± 0.41^{a}	0.8937
b*	14.52 ± 0.25^{a}	12.81 ± 0.87^{b}	13.34 ± 1.45^{ab}	0.3671
C*	15.13 ± 0.26^{a}	14.19 ± 0.82^{a}	14.60 ± 1.49^{a}	0.2434
H*	73.66 ± 0.18^{a}	64.55 ± 1.34^{b}	65.92 ± 0.98^{b}	0.9878

Mean value ± standard error (n = 3). [a-c]Different superscript letters on the same row indicate significant differences among samples (P < 0.05). ADP: Acheta domesticus powder; TMP: Tenebrio molitor powder; LMP: Locusta migratoria powder.

(Lucas-González et al., 2019; Vanqa et al., 2022). TMP showed the highest pH value and LMP the lowest ($P < 0.05$). These pH values (near to neutrality) make these insect powders suitable for addition to different food matrices (meat, dairy, bakery, etc.) where not important structure modifications will be expected.

The color of food ingredients has an important technological relevance due to the influence on the final food color and its effect on the consumer acceptance (Kouřimská and Adámková, 2016; Rodríguez-Párraga et al., 2025). The most affected coordinate was lightness, which values ranged from 34 to 50 ($P < 0.05$) being ADP the lightest and LMP the darkest. This low L* values, would suggest that their inclusion as food ingredients would cause the product to darken, which should be evaluated to avoid consumer rejection. Regarding redness, TMP and LMP showed the highest a* values (without differences between them) and ADP the lowest ($p < 0.05$). On the contrary, ADP showed the highest b* values and TMP the lowest. The color of the insect powders is due to their content in several pigments, mainly carotenoids (yellow, orange and red components) and melanin (browns and black compounds), and also to others compounds such as chitin that, although not a pigment in itself, its presence can affect the texture and color of the powder, giving it a duller or earthier appearance (Omuse et al., 2024). In addition, the technological process applied to obtain the powders (temperature, dry method, milling, etc.) can also affect the resulted color (Guiné, 2018). There were not differences in saturation (C*) between the three insect powders ($P > 0.05$).

Fig. 3 shows the reflectance spectra (corresponding to the range of the human visual spectrum) of the three insect powders. It can be seen that the 3 insect powders showed the same spectrum shape, but with different reflectance percentages: LMP showed the lowest reflectance values and ADP the highest ($P < 0.05$), at all wavelengths. In addition, it is important to highlight that the differences in the reflectance values (%) between TMP and LMP were lower (1.5- 5 %) than with ADP (3.5–10.3 %).

3.6. Techno-functional properties

The techno-functional properties (WHC, OHC, SWC, EA, GC and ES) help predict the technological feasibility of incorporating a new ingredient in the food development process, in terms of its behavior and interactions with the food matrix components (water, lipids, carbohydrates and fibers) (López-Marcos et al., 2015). In addition, all these techno-functional properties affect the texture and the flavor of the resulted foods. The η^2 values for all the techno-functional properties indicated large size effects (ranging between 0.7379–0.9842) except for SWC (0.0133, small effect). SWC and WHC are related to the ability to take up and to retain water, respectively, and OHC is related to the ability to retain oil. Although there were not differences ($P < 0.05$) in SWC between the three insect powders, LMP showed lower ($P < 0.05$) WHC and OHC than ADP and TMP (Fig. 3). These results could indicate that although LMP has a similar ability to absorb water (swelling) than the other powders, it is not totally retained by the structural components and so its WHC was lower. The WHC and OHC in flours have been mainly related to the protein content, but not only to the amount of protein but also to its state (hydrophilic/hydrophobic balance, spatial structure (tertiary and quaternary), state (native or denatured), etc.) (López-Marcos et al., 2015). The WHC and OHC values obtained for ADP and TMP are into the range reported by several authors for insect-based flours from the same species (*T. molitor*: WHC: 1.3 – 2.8 g/g; OHC: 1.1 – 1.7 g/g; *A. domesticus*: WHC: 1.8 - 3.8 g/g; OHC: 1.6 - 2.2 g/g) (Aguilera et al., 2021; Borremans et al., 2020; Brena-Melendez et al., 2024; Lucas-González et al., 2019; Udomsil et al., 2019; Zielińska et al., 2018). No references have been found about these properties in L. *migratoria* derived flours. The WHC and OHC values obtained for insect powders are into the range of reported for other alternative protein sources such as legumes (Huamaní-Perales et al., 2024). For example, some pea varieties exhibited WHC values between 2.4–2.8 g/g and faba bean exhibited OHC values near to 1.0 g/g. Ingredients with high WHC are desirable for foods like minced meats or analogues, baked doughs, dairy products, and custards because they help preserve moisture and the feeling of freshness. High OHC ingredients are also specifically suited for use in fatty matrices such as sausages and dressings (López-Marcos et al., 2015). So, both ADP and TMP would seem more appropriate than LMP for these purposes.

There are a lot of foods that physico-chemically are considered colloids, mainly emulsions and gels (mayonnaise, salad dressing, backed goods, dairy desserts, jams, yogurts, cheeses, pâté, and Frankfurt-type sausages among others). So, the effect that some food ingredients could have in the formation and stability of food emulsions or food gels

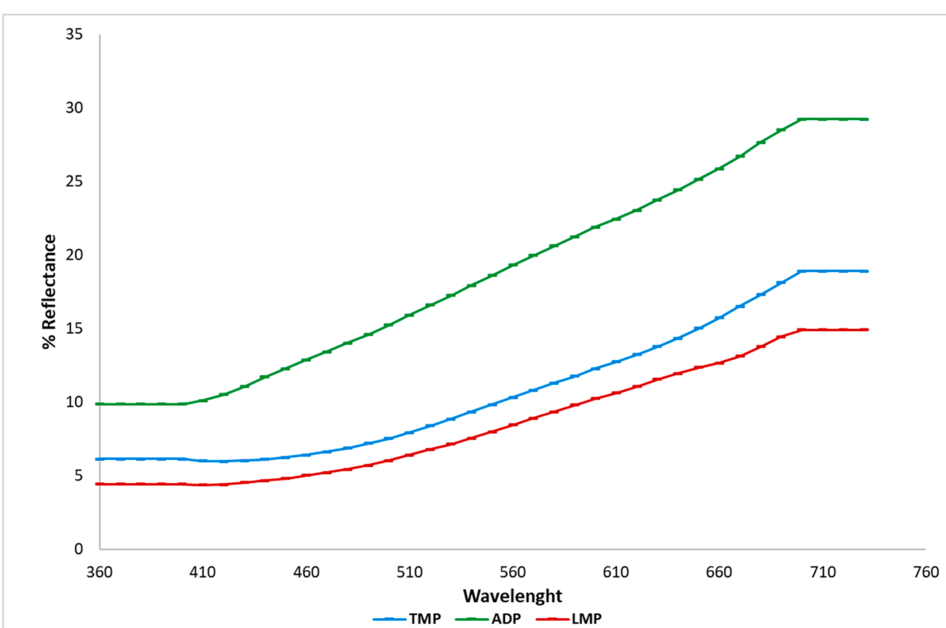

Fig. 3. Reflectance spectra (% reflectance) between 360–740 nm of edible insect powders. n = 3; ADP: A. domesticus powder; TMP: T. molitor powder; L. migratoria powder.

should be addressed, previously to its incorporation in the selected food, in order to avoid structure breakage or destabilization during the food shelf life. As can be seen in Fig. 3, the three insect powders showed values higher than 50 % for EA and GC, which means that they could be successfully used for these purposes. LMP showed the highest values ($P < 0.05$) for both properties (EC and GC), reaching GC values near to the maximum (>93 %), and ADP the lowest ($P < 0.05$). Regarding ES, also in this case LMP showed the highest values (>99 %) followed by ADP and TMP ($P < 0.05$). Emulsion capacity and stability have been related to the amphiphilic nature of the proteins (ratio between hydrophilic and hydrophobic amino acids) and the secondary structure of the protein (Lam and Nickerson, 2013). For common legumes these values varied in the following ranges: EC 60–90 % and ES 66–99 % (Huamaní et al., 2024). LMP showed ES values similar to conventional reference ingredients such as whey (100 % ES), egg (95 % ES) and soy (100 % ES) (Stone et al., 2015). These values are usually higher in protein extracts than in flours or powders because the extraction process modify these parameters and alter the protein structure (breakdown of large protein molecules and the exposure of the hydrophobic amino acids) (Zielińska, 2022). For this reason, the high GC and ES values reached by LMP are remarkable, considering that is a powder obtained directly after the grinding of the whole insect without any other extraction process. This insect powder (LMP) would seem to be more suitable for the development of emulsion-based food systems such as milk. Mayonnaise, emulsified condiments, salad dressing, sausages and ice cream. (Fig. 4)

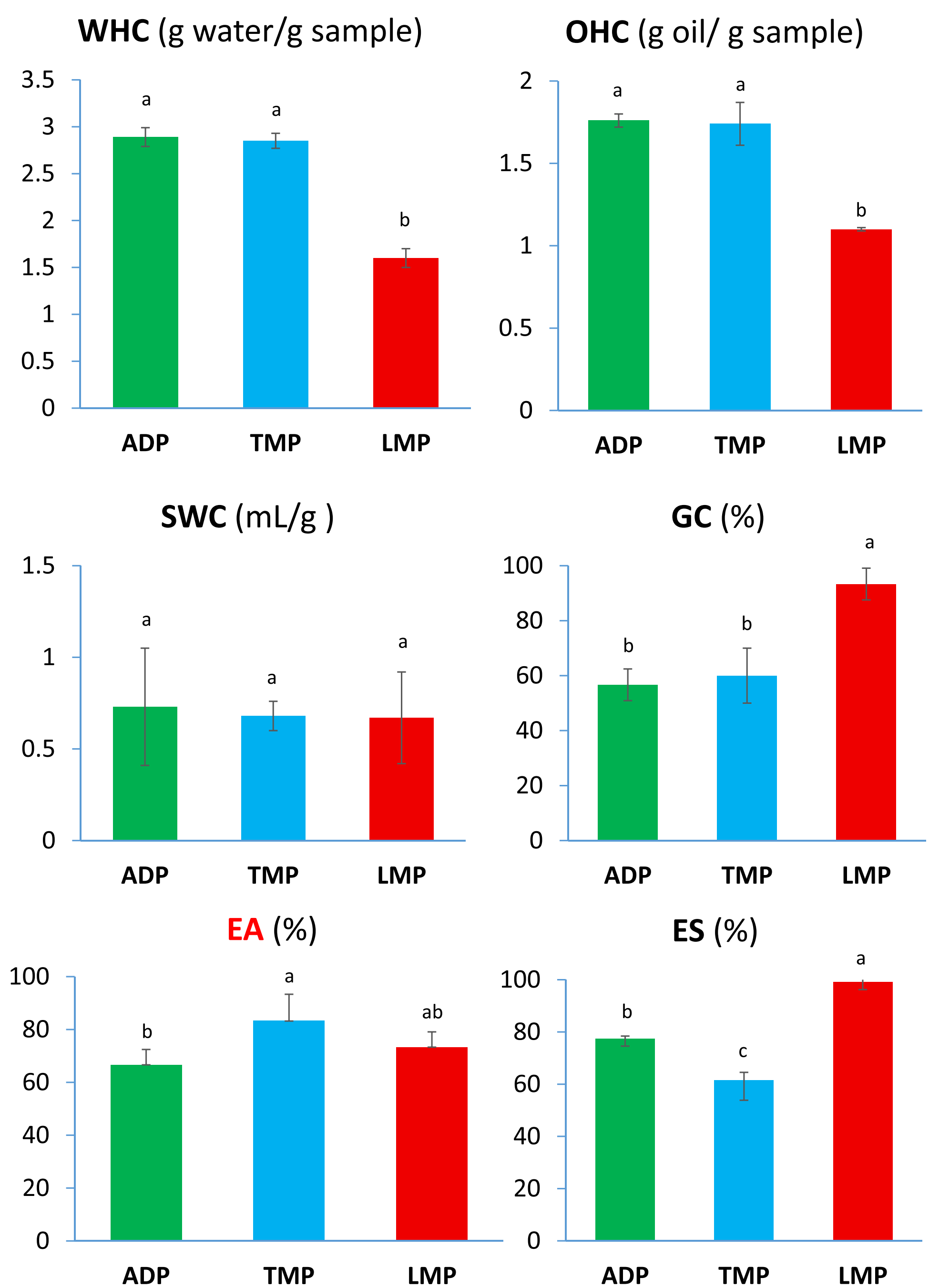

Fig. 4. Techno-functional properties [WHC: water holding capacity (g water/g sample); OHC: oil holding capacity (g oil/g sample; SWC: swelling capacity (mL/g); GC: gelling capacity (%); EA: emulsifying activity (%); ES: emulsion stability (%)] of edible insect powders. [(a-c)] Different letters indicate significant differences among samples ($P < 0.05$) ($n = 3$). ADP: A. domesticus powder; TMP: T. molitor powder; L. migratoria powder.

3.7. Antioxidant properties

Several authors have reported that edible insects are promising sources of bioactive molecules with antioxidant properties (Baek et al., 2019; Botella-Martínez et al., 2020). These antioxidant properties have been related not only to their content in phenolic compounds, but also to other compounds such as alkaloids, terpenoids, bioactive peptides derived from their high protein content, chitosan, and even to fatty acids (Di Mattia et al., 2019; Hall and Liceaga, 2020; Psarianos et al., 2025; Torres-Castillo and Olazarán-Santibáñez, 2023). The antioxidant activity of insect powders was evaluated applying 3 methods trying to compile the different antioxidant mechanisms: DPPH as a measure of the ability to neutralize free radicals, FRAP as a measure of the reducing capacity of the sample, and FIC as a measure of the ability to bind iron ions (Fig. 5). The η^2 values for the 3 antioxidant methods applied indicated large size effects (ranging between 0.9809–0.9842). As can be seen in Fig. 5, ADP and TMP showed the highest DPPH values (without differences between them; $P > 0.05$), while LMP showed the highest FRAP and FIC values ($P < 0.05$). The highest differences between samples can be observed in the reducing capacity (FRAP method), showing LMP 10-fold higher FRAP values than TMP. In general (and considering the results of the three methods evaluated), it could be said that LMP showed the best antioxidant activity, followed by ADP, and TMP. Di Mattia et al. (2019) also reported higher antioxidant activity (by several methods) in extracts from house cricket than from mealworm. D'Antonio et al. (2023) reported that edible insects (the aqueous extracts and digesta of silkworms, grasshoppers, mealworms and giant worms) displayed significantly higher *in vitro* antioxidant activity than some common legumes (lentils and chickpeas). Moreover, edible insects at all tested concentrations were able to exert an antioxidant effect in a cellular model (cells of human colonic mucosa), while legumes were effective mainly at high concentrations. Ivanišová et al. (2023) used different insect meals (L. *migratoria, T. molitor, A. domesticus*) to produce crackers, observing higher antioxidant activity when L. *migratoria* was used.

Several authors have also reported that the antioxidant activity could be increased when these insect-based powders are subjected to some technological process. For example, Navarro del Hierro et al. (2021) observed higher antioxidant activity after defatting *T. molitor* larvae meal (50% DPPH inhibition) compared to using the non-defatted biomass (40 % DPPH inhibition). Muñoz-Seijas et al. (2025) reported that microwave assisted extraction (MAE) was the most effective pre-treatment (in comparison to ultra-sound-assisted extraction-UAE, microwave-assisted extraction-MAE, temperature-assisted extraction-TAE, and CO_2-assisted extraction) to release phenolics and antioxidant activity from the biomass of *T. molitor* beetles. These pre-treatments would be inducing conformational alterations in proteins modifying their antioxidant properties Indeed, higher antioxidant activity (up to around 38 % ABTS scavenging activity) was observed in proteins obtained after pre-treatment of defatted *T. molitor* meal, compared to a native protein (Hoon Lee et al., 2024).

3.8. Principal component analysis (PCA)

PCA is an unsupervised method of data reduction that allows integration and visualization the relationship between all the analyzed variables in the insect powders. Fig. 6 displays the spatial distribution of the samples in the two-dimensional space defined by the first two principal components. The first component (PC1) accounted for 52.44 % of the total variation, while the second component (PC2) explained 38.00 %, together representing >90 % (90.44 %) of variability. LMP was plotted on the negative axis of both components (PC1 and PC2), showing a strong positive association with parameters such as water activity, mineral profile, some amino acids content (hydroxyproline, alanine, glycine and methionine) and some fatty acids (C16:0, C18:0, C18:3, n3 and n6). In contrast, ADP was plotted on the positive axis of PCA1 but on the negative axis of PCA2, showing positive correlations with WHC, OHC, L*, some amino acids (tyrosine, histidine, serine and phenylalanine), and some fatty acids (C16:0, C18:0, C18:3, n3 and n6). In turn, TMP was mainly clustered on the positive axis of both PCA1 and PCA 2, but showing stronger correlations with the PC2 variables (moisture and fat content, emulsion stability and fat profile (C12:0, C14:0, C16:1, C18:1 *cis*, MUFA, TI, AI). In addition, the closeness between the samples of each insect is indicative of how robust the analysis is. Overall, the PCA biplot confirms that the three insect powders analyzed are significantly different in most of the analyzed parameters. Moreover, the spatial distribution differences among the three insect powders studied (LMP, ADP and TMP) highlight the differences between them and the importance of selecting the appropriate insect powders according to the goal (technological, nutritional, health, etc.) of the new food.

4. Conclusions

This work provides a thorough analysis of the nutritional content, techno-functional, physicochemical and antioxidant properties of powders derived from three edible insect species, with a particular focus on their potential food applications. The studied edible insect powder species were rich in protein, with varying levels of fat and dietary fiber

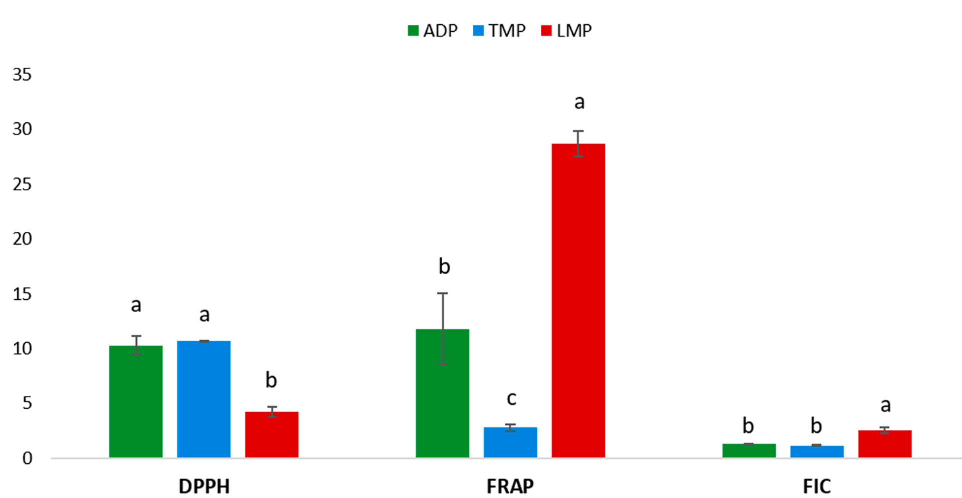

Fig. 5. Antioxidant activity [DPPH: 2,2-diphenyl-1-picrylhydrazyl (mg Trolox equivalent/g); FRAP: Ferric reducing antioxidant powder (mg Trolox equivalent/g); FIC: Ferrous ion chelating (mg EDTA equivalent/g)] from edible insect powders. [(a-c)] Different letters on the same antioxidant method indicate significant differences among samples (P < 0.05) (n = 3). ADP: A. domesticus powder; TMP: T. molitor powder; L. migratoria powder.

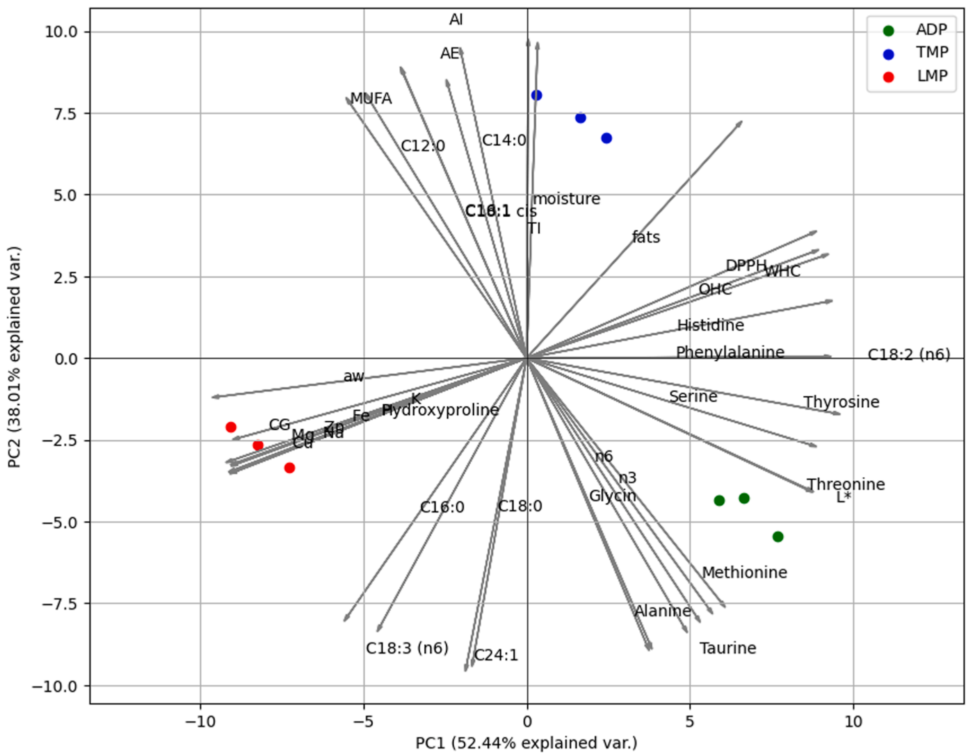

Fig. 6. Principal component analysis (PCA) biplot and component loadings (evaluated parameters). ADP: A. domesticus powder; TMP: T. molitor powder; L. migratoria powder.

depending on the species. Their dietary fiber content is a distinguishing feature compared to other sources of animal protein (meat, fish, milk or eggs), which lack dietary fiber. Notably, the amino acid profiles of TMP and ADP meet the FAO requirements for adults, making them comparable to traditional animal-based protein sources, while LMP showed some limiting amino acids. Furthermore, the fatty acid profiles reveal a higher content of UFA than SFA in all samples, and beneficial PUFA/SFA ratio, indicating their potential as a healthy fat source in the diet. The diverse mineral content, mainly in ADP and TMP, suggests that insect powders could help address mineral deficiencies in human diets. Specifically, TMP is an excellent source of Mg, LMP of Zn and both of them are good sources of Fe.

Beyond their nutritional value, the study underscores the significant techno-functional and antioxidant properties of these insect powders, highlighting their suitability for various food applications. The physicochemical characteristics, such as water activity and pH, indicate their stability and compatibility with different food matrices. Their colorimetric properties would indicate that significant color changes are likely to occur in foods to which they are added, so measures should be explored to ensure that such changes are not viewed negatively by consumers. Their techno-functional properties, including emulsion and gelation capacities, suggest their potential as effective ingredients for structuring and stabilizing processed foods, especially LMP. Moreover, their antioxidant properties are particularly interesting, as these properties can contribute to both human or animal nutrition and the preservation of food products by preventing lipid rancidity during storage and processing. In this sense, LMP displayed the best antioxidant activity, followed by ADP, and then TMP. The distinct profiles observed among the three insect species emphasize the importance of selecting the appropriate insect powder based on the specific nutritional, technological, or health-related goals for novel food development or even to design appropriate mixtures of these insect powders, in order to achieve the desired characteristics according to the type of food to which they are to be added.

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Ethical statement

This research does not involve humans o animals. The insects used were purchased from Insectum (Valencia, Spain), an authorized company to sell insects for human consumption.

CRediT authorship contribution statement

Judit Rodríguez-Párraga: Writing – original draft, Methodology, Formal analysis. **Raquel Lucas-González:** Writing – review & editing, Supervision, Data curation, Conceptualization. **Carmen Botella-Martínez:** Writing – original draft, Validation, Methodology. **Manuel Viuda-Martos:** Writing – review & editing, Validation, Resources, Conceptualization. **José Manuel Lorenzo:** Writing – review & editing, Resources, Formal analysis. **Fernando Borrás-Rocher:** Writing – review & editing, Validation, Formal analysis. **José Ángel Pérez-Alvarez:** Writing – review & editing, Validation, Resources. **Juana Fernández-López:** Writing – review & editing, Supervision, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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