Dehydration-Induced Changes in physical and volatile characteristics of house cricket (Acheta domesticus) powder

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Dehydration-induced changes in physical and volatile characteristics of house cricket (*Acheta domesticus*) powder

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ABSTRACT

This study evaluated changes in the physical properties of cricket powder during dehydration, under parameters consistent with EFSA scientific opinions and wider international practices. Freeze-drying for 24 h resulted in cricket powder with 3.96 g/100 g moisture content and a_w of 0.237. In oven-dried crickets, greatest moisture loss occurred within the first 3 h across all temperatures evaluated. Significant colour changes were noted in dried cricket powders, lightening was attributed to metalloprotein deoxygenation, while increased darkening indicated the occurrence of non-enzymatic browning, supported by the appearance of Maillard reaction products. ATR FT-IR showed significant peak shifts indicating dipole-active vibrational changes, while Amide I deconvolution revealed an unchanged protein secondary structure. Concentration of volatile compounds increased as function of dehydration time, attributable to Strecker degradation, Maillard and lipid oxidation reactions. In conclusion, dehydration alters cricket powder attributes that may require adjustments for optimised processing or subsequent macromolecule extraction.

1. Introduction

The house cricket (*Acheta Domesticus*) is one of four insect species currently approved for human consumption in the European Union (IPIFF, 2025). Cricket powder forms approved as novel foods in Europe are currently limited to partially defatted oven-dried powder and freeze-dried powder.

Research to date has applied different dehydration parameters to cricket powders for a variety of purposes, such as microbial testing, nutritional testing and sensory testing (Bawa et al., 2020a; Khatun et al., 2021; Ribeiro et al., 2022). However, changes in the physical characteristics of crickets as dehydration proceeds, using the two approved novel food dehydration processes as a guide, have not been studied and may be instrumental in directing targeted adjustments for improved onward processing outcomes or the extraction of cricket powder macromolecules for food applications.

Dehydration is a widely used unit operation applied to remove the majority of water present in food under controlled conditions, either by evaporation or sublimation. Its main purpose is to extend the shelf-life of foods by reducing their water activity (a_w). The dehydration processes recommended in Europe for the production of powders are freeze-drying to a final moisture content of <5 % and oven-drying for at least 6 h at <90°C, until a final moisture content of <6 % (Turck et al., 2022; Turck et al., 2021). However, wider international processing temperatures up to 110°C have been reported in the literature (Fröhling et al., 2020). Oven-drying, particularly at higher temperatures, enables faster moisture removal, which makes it a practical method for industrial applications, but may cause detrimental change to attributes (colour, protein structure, thermal behaviour and volatile accumulation), potentially affecting the quality and application of the dehydrated product or ingredient. Freeze-drying, by contrast, operates at low temperatures under vacuum, and may preserve the integrity of the end-product, but is slower and likely to be more costly (Adams & Moss, 2007; Ratti, 2001).

The aim of this study was to use a timed approach to monitor the effect of dehydration processes (freeze-drying and oven-drying) on the physical characteristics of house cricket powder (moisture content, water activity, colour, protein structure, thermal behaviour and volatile accumulation), in order to generate data that inform subsequent food formulations. It was hypothesised that oven-drying would reduce drying time, but with detrimental change to physical attributes, while freeze-drying would preserve these at the expense of extended drying times.

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2. Materials and methods

2.1. Materials

House crickets (*Acheta domesticus*) were supplied by the UK Insect Company Ltd (trading as Edibl®). Four batches of crickets, harvested at 5-weeks, and fasted for 48 h prior to euthanisation by freezing, were pooled together and stored at -20°C until further use.

Solid-phase microextraction standards were obtained from Sigma-Aldrich (Gillingham, UK): 1,2-dichlorobenzene (10 mg/L) and alkane standards C6-C25 (100 µg/mL) in diethyl ester. Sodium chloride was obtained from Fisher Scientific (Loughborough, UK).

2.2. Dehydration of whole house crickets

Frozen whole house crickets were used as a control sample. Additionally, whole frozen house crickets were oven dried and freeze dried. For the former, the oven (Salvis Thermocenter TC40S) was preheated to the desired temperature (80°C, 90°C or 100°C). The air outlet was set to maximum and air flow rate to 80 % (estimated airflow rate ~1.89 m^3/h). Frozen whole house crickets (15 g) were spread evenly on foil dishes and loaded immediately into the pre-heated oven. Three dishes of crickets were removed from the oven, at hourly intervals, up to 6 h. In the case of freeze-drying, frozen whole house crickets (15 g) were added into Sterilin pots and added into a freeze-dryer (Scanvac Coolsafe, LaboGene ApS, Denmark). Three pots of crickets were removed from the freeze-drier at 8 hourly intervals, up to 24 h. After dehydration, samples were directly transferred to a desiccator, used immediately for analysis of water content, water activity and colour, with any residual stocks subsequently stored in parafilm-sealed Sterilin Polypropylene pots at −20°C. Samples were ground, immediately prior to analysis, on the fine setting of a burr grinder (Krups GVX2, Groupe SEB, France), resulting in powders with a particle size of less than 600 µm.

2.3. Analytical methods

The moisture content of fresh and dehydrated cricket samples was determined using a halogen moisture analyser (Mettler Toledo HE53). Ground samples (~0.5 g), were evenly spread on the pan, placed in the analyser and dried under a halogen lamp at 105 °C until consistent weight was achieved and the moisture content was recorded.

The water activity (a_w) of the samples was determined using a water activity meter (Rotronic Hygrolab, with single probe). Ground samples were placed in small sample cups, with sufficient quantity to cover the bottom of the cup, with lid secured and left to equilibrate to room temperature (18–19°C). They were then placed in the chamber to initiate the analysis. The water activity (a_w) and analysis temperature values were recorded for each sample when analysis was complete.

The colour of fresh and dehydrated cricket samples was determined using a handheld CR-400 Chroma Meter (Konica Minolta, USA), calibrated on a white tile. Ground samples were placed in small sample cups, with sufficient quantity to cover the bottom of the cup, and the cups were placed on a black tile while colour analysis was conducted. Colour quantification was conducted using the CIELAB system with the values for lightness (L*), red/green coordinate (± a*) and yellow/blue coordinate (± b*) recorded.

These values were used to calculate overall change in colour using the following equation (Eq. 1):

$$E^*_{ab} = \sqrt{\left(L^*_2 - L^*_1\right)^2 + \left(a^*_2 - a^*_1\right)^2 + \left(b^*_2 - b^*_1\right)^2} \tag{1}$$

For the browning index (Buera, 1986; Fröhling et al., 2020), the following equation was used (Eq. 2):

$$BI = 100 * \left(\frac{X - 0.31}{0.17}\right) \tag{2}$$

Where the intermediate value X, was calculated as per the equation below (Eq. 3):

$$X = \frac{a^* + 1.75L^*}{5.645L^* + a^* - 3.012b^*} \tag{3}$$

2.4. Attenuated total reflectance Fourier-transform infrared (ATR FT-IR) spectroscopy analysis

The molecular composition of the fresh and dehydrated cricket samples was assessed with ATR FT-IR. The spectra were collected on a Perkin-Elmer Spectrum 100 FTIR spectrometer, fitted with an attenuated total reflectance (ATR) device with a diamond crystal. Samples were analysed in the region of 4000–650 cm^{-1} at a resolution of 4 cm^{-1} with 64 scans and were automatically recorded against a background spectrum from the clean empty cell at room temperature.

Deconvolution was carried out using the "Peak Analyse" function in OMNIC 8.0 (Thermo Fisher Scientific Inc., Waltham, MA, USA) software. The settings used to select the peaks were Gaussian/Lorentzian, high sensitivity, baseline selection "none" and FWHM "6.5″ (Susi & Byler, 1986). Prior to fitting, spectrum noise was assessed at a flat central region in the spectrum and used as the "noise target".

2.5. Thermogravimetric analysis (TGA)

Thermogravimetric analyses of cricket samples were carried out with a TGA Q50 thermogravimetric analyser (TA Instruments, New Castle, DE, USA). Around 0.5 mg of each sample was placed in an aluminium pan and heated from 20°C to 450°C with a 10°C/min ramp, under nitrogen at 60 mL/min flow rate.

2.6. Volatile analysis using solid-phase microextraction followed by gas chromatography-mass spectrometry (SPME GC–MS)

Semi-quantification of the volatile compounds in the fresh and dehydrated cricket samples was carried out by automated headspace solid-phase microextraction (SPME) followed by gas chromatography-mass spectrometry (GC–MS), using a 110 PAL injection system and Agilent 7890 gas chromatograph with 5975C mass spectrometer (Agilent, Santa Clara, CA, USA). Ground cricket samples (5 g fresh crickets or 1.5 g oven dried or freeze-dried crickets), together with a salt solution to promote partitioning of volatiles into the headspace (1 mL distilled water, 1.5 g NaCl) and 20 µL 1,2-dichlorobenzene in methanol (10 mg/L) as internal standard, were weighed into a 20 mL SPME vial fitted with a screw cap and vortexed for 1-minute. After equilibration at 70°C for 20-minutes, a 50/30 µm DVB/CAR/PDMS fibre (Supelco, Bellefonte, PA, USA) was exposed to the headspace above the sample for 30-minutes at 70°C. After extraction, the fibre was desorbed for 20-minutes. For the chromatographic separation, a ZB-Wax column, 30 m x 250 µm x 1 µm (Phenomenex Inc., Torrance, CA, USA), was used. The oven temperature programme used was 10-minutes at 40°C isothermal and an increase of 4°C/min to 240°C, held for a final 10-minutes. Helium was used at 0.9 mL/min as carrier gas. The mass spectrometer operated in electron impact mode, with a source temperature of 230°C, an ionising voltage of 70 eV, and a scan range from *m/z* 29 to 400 with 1.9 scans/s. The obtained chromatograms were analysed in MSD ChemStation 2011 and the compounds relating to peaks on the chromatogram were tentatively identified by comparison of each mass spectrum with spectra from authentic compounds analysed in our laboratory, or from the NIST mass spectra library (NIST 2020) or spectra published elsewhere. To confirm identification, *n*-alkanes C_6-C_{25} (100 µg/mL) in diethyl ester were analysed under the same conditions and used to calculate the linear retention index (LRI) for each compound to compare to LRI values of authentic compounds analysed in similar conditions. A spectral quality value of >70 was used alongside a published linear retention index (LRI) to support the identification of compounds where no internal authentic standards were available. The approximate quantification of volatile compounds was calculated from GC peak areas, by comparison with the peak area of the 1,2-dichlorobenzene standard, using a response factor of 1.

2.7. *Statistical analysis*

Quantitative differences between samples were analysed with XLSTAT (Version 2022.5.1.1388. Paris, France). Freeze-drying data were analysed using a one-way analysis of variance (ANOVA) based on treatment, whereas oven-drying data were subjected to a two-way ANOVA to account for the effects of both time and temperature. A separate one-way ANOVA was conducted for volatile compound profiles across all treatments. Tukey's honest significant difference (HSD) test was applied for multiple pairwise comparisons. In multiple pairwise comparisons, significance was assumed at $p \leq 0.05$. Principle component analysis (PCA) was used to qualitatively visualise graphically the differences between samples in the volatile compound analysis. Unless otherwise stated, all reported results represent the mean ± standard deviation of three independent samples (n=3), each analysed twice.

3. Results and discussion

3.1. *Effect of dehydration on moisture content and water activity of cricket powders*

The initial mean moisture content of untreated crickets was 64.89 ± 2.5 g/100 g which falls close to the median of the range published by Ververis et al. (2022) and the values reported by Ritvanen et al. (2020) for crickets aged 4.5 weeks at harvest (69.1 ± 4.5 g/100 g fresh weight). The initial mean a_W of untreated crickets was 0.991 ± 0.003. Bawa et al. (2020a) reported an initial a_w of 0.89 ± 0.01 for 7-week old crickets, which is considerably lower, but may be explained by an overnight defrosting step prior to analysis where cell and tissue fluid loss might account for the difference (Gonçalves, 2009).

To limit microbial spoilage during storage, it is recommended that dehydrated foods reach microbial stability at $a_W < 0.6$ (Adams & Moss, 2007). The two dehydration methods applied (oven drying and freeze drying) successfully reduced a_w to <0.6 in 3 h at 80°C, in 2 h at 90°C and 100°C, and after 24 h in the case of freeze-drying (Figs. 1 and 2). These conditions achieved the EFSA recommended moisture content of <6 % (w/w) in oven-dried house crickets and <5 % (w/w) in freeze-dried crickets (Turck et al., 2022; Turck et al., 2021). Khatun et al. (2021) demonstrated that by increasing the surface area of house crickets via grinding prior to freeze-drying, a lower final moisture content was obtained (1.27 ± 0.10 %), but at extended drying periods (40 h).

In oven drying, extending the drying time to 6 h as suggested by EFSA, resulted in a lower a_w (<0.3). Bawa et al. (2020a) reported a final moisture content of 5 % (w/w) after 4 h at 80°C and an a_w of 0.40 in defrosted, oven-dried crickets. These values were higher than those obtained in the current study; this could be due to the fact that the initial moisture of the crickets used in Bawa et al. (2020a) was higher, but also due to size and age of crickets (older and larger), water absorption occurring during blanching, or potentially a slower drying rate due to larger sample batches (200 g versus 15 g in the current study). These points suggest that scaling up of cricket powder processing for commercial production, could require extended dehydration periods even at higher temperatures.

3.2. *Effect of dehydration on house cricket colour*

In untreated cricket samples (control), the CIELAB colour parameters L*, a*, and b* were 42.06 ± 0.83, 3.22 ± 0.38 and 6.78 ± 0.65 respectively. Bawa et al. (2020a) reported values of 22.67 ± 0.80, 2.47 ± 0.04, 4.41 ± 0.02, 5.06 ± 0.02 indicating that their crickets were darker, less red and less yellow compared to the current study. The variation for these differences could be due to defrosting prior to analysis. Specifically, drip loss occurring due to the physical disruption of the structure caused by ice-crystals, has been shown to affect meat colour due to protein oxidation (Traore et al., 2012). Equally, the age of the crickets used in the analyses may have an effect; larger crickets in the *Allonemobius socius* species have been shown to be dependent on darker cuticles for body temperature regulation (Fedorka et al., 2013).

Freeze-drying resulted in a significant increase in L* (lightness) at 16 h (Table 1), but no further significant changes were noted beyond that time point. Water removal and particle size affect light scattering and the luminosity L* values (Nabil et al., 2020). Our results differ to those reported by Khatun et al. (2021); specifically, ground freeze-dried crickets (for 40 h) had an L* value of 66.29 ± 0.55. It is suggested that the lower final moisture content achieved in Khatun et al. (2021) (1.27 %) could potentially have affected the light scattering. In this study, the notably positive increase in b* (yellow direction) at 16 h may be explained by the presence of hemocyanin in arthropods, a respiratory oxygen carrier protein present in their haemolymph (Brogan et al., 2021; Burmester, 2001; Nowosielski & Patton, 1965). On binding to oxygen, it appears deep blue (Van Holde, 1967), but on release of oxygen it is clear. The removal of oxygen under vacuum during freeze-drying may have increased the quantity of clear hemocyanin, explaining a positive shift in the yellow direction (HunterLab, 2024). Conservation of the protein structures during freeze-drying may enable colour change under poor storage conditions or during application to a food matrix where further physical and chemical interactions may occur.

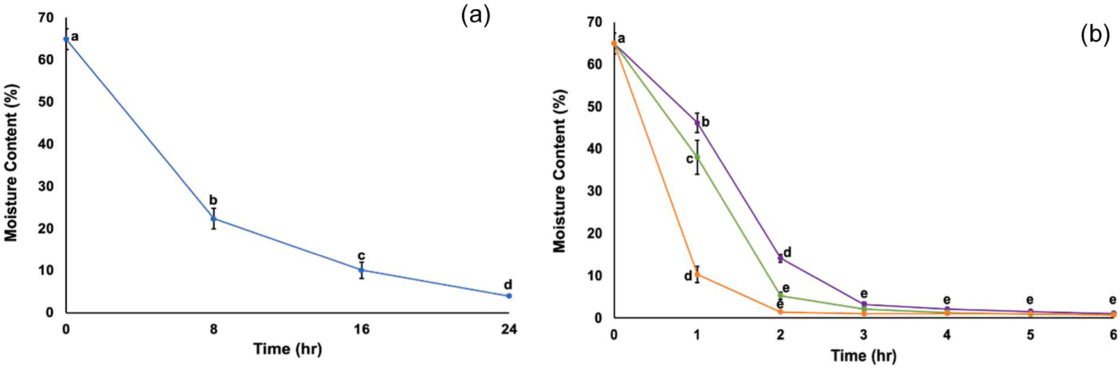

Fig. 1. Moisture content of (a) freeze-dried and (b) oven-dried house crickets.
—●— 80°C, —●—90°C, —●—100°C; n=3 ± std dev; values with different letters are significantly different to each other ($p \leq 0.05$).

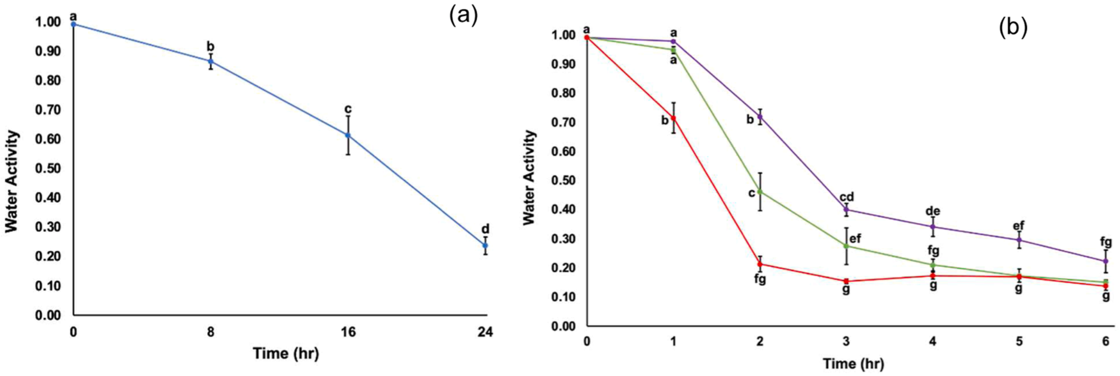

Fig. 2. Water activity of (a) freeze-dried and (b) oven-dried house crickets.
—●— 80°C, —●—90°C, —●—100°C; n=3 ± std dev; values with different letters are significantly different to each other ($p \leq 0.05$).

Table 1
Colorimeter analysis for lightness (L*), red/green direction (a*), blue/yellow direction (b*) of freeze-dried house crickets.

Time (h)	CIELAB values L* (lightness)	a* (red/green)	b* (yellow/blue)
0	42.06 ± 0.83^{a}	3.22 ± 0.38	6.78 ± 0.65^{a}
8	40.01 ± 4.11^{a}	3.43 ± 0.05	8.77 ± 1.72^{a}
16	51.13 ± 2.30^{b}	3.43 ± 0.31	12.99 ± 0.09^{b}
24	53.01 ± 0.63^{b}	3.28 ± 0.19	13.86 ± 0.22^{b}

Results are means of three independent replicates (n=3) ± standard deviation; values with different letters are significantly different to each other $p \leq 0.05$

Table 2 shows the CIELAB colour space values for the oven-dried crickets Results show a significant reduction in L* (lightness) in all samples, and a significant change to a* (redness) and b* (yellowness) in samples dried at 100°C compared to untreated crickets. Colour change appears to stabilise when a moisture content of <5 g/100 g and $a_w < 0.6$ is achieved (3 h at 80°C, 2 h at 90°C and 100°C). These values have been used to calculate the overall change in colour, E^*_{ab}, which highlights the presence of a significant and noticeable change in colour.

These values have been used to calculate the browning index (Table 3). Increasing values provide a simple indicator of non-enzymatic browning (Maillard reaction and caramelization).

Cricket powder is rich in lysine, which is a key precursor for browning. Oven-drying of crickets at (≤100°C), appears to trigger several reactions (Maillard reactions, lipid oxidation, and thermal degradation) contributing to colour change, potentially through melanoidin formation, with greater darkening occurring at increased temperatures. The stabilisation of the browning index correlates to a reduction in a_w to below 0.5, indicating that dehydration passes swiftly through a critical a_w range (0.8–0.5) such that colour formation is limited due to reduced mobility of the precursors (Ames, 1990). Notably, the addition of oven-dried cricket powder in food matrices has been reported to negatively impact the colour of the final products (Cavalheiro et al., 2023; Grossmann et al., 2021), with significant darkening of colour occurring with increasing powder inclusion. While part of this may be attributed to the colour of the cricket powder itself, research has shown that after oven-drying, house crickets retain a considerably significant level of protein, which affect the intensity of browning to different extents (Ames, 1990; Ashoor, 1984). Consequently, the food matrix to which cricket powder is added, may have to be adjusted to minimise the occurrence of the Maillard reaction, in particular with regards to reducing sugar content (Ashoor, 1984) and pH value (Fan et al., 2023).

Table 2
Data from colorimeter analysis for lightness (L*), red/green direction (a*) and blue/yellow direction (b*) of oven-dried crickets.

Time (h)	L* 80°C	90°C	100°C
0	42.06 ± 0.83^{a}		
1	27.43 ± 3.33^{fg}	27.33 ± 0.93^{g}	31.15 ± 0.70^{cdefg}
2	34.23 ± 0.88^{bcd}	35.13 ± 1.36^{bc}	35.76 ± 0.09^{b}
3	34.36 ± 2.90^{bcd}	32.37 ± 2.07^{bcde}	33.05 ± 1.31^{bcde}
4	31.88 ± 0.76^{bcdef}	31.12 ± 0.87^{cdefg}	33.13 ± 0.81^{bcde}
5	29.69 ± 1.31^{efg}	29.94 ± 1.60^{defg}	32.55 ± 0.51^{bcde}
6	29.90 ± 1.48^{defg}	29.97 ± 1.16^{defg}	33.35 ± 0.78^{bcde}
Time (h)	**a***		
	80°C	**90°C**	**100°C**
0	3.22 ± 0.38^{cdef}		
1	1.43 ± 0.09^{h}	2.26 ± 0.30^{gi}	2.92 ± 0.22^{efg}
2	2.41 ± 0.16^{fg}	3.19 ± 0.17^{def}	4.14 ± 0.15^{a}
3	3.30 ± 0.13^{bcde}	3.66 ± 0.13^{abcde}	4.17 ± 0.25^{a}
4	3.16 ± 0.05^{def}	3.82 ± 0.32^{abcd}	4.08 ± 0.18^{ab}
5	3.17 ± 0.04^{def}	4.03 ± 0.35^{abc}	4.32 ± 0.19^{a}
6	3.17 ± 0.10^{def}	3.65 ± 0.39^{abcde}	4.27 ± 0.64^{a}
Time (h)	**b***		
	80°C	**90°C**	**100°C**
0	6.78 ± 0.65^{cde}		
1	3.14 ± 0.04^{g}	4.19 ± 0.96^{fg}	6.46 ± 0.19^{de}
2	5.76 ± 0.57^{ef}	7.49 ± 0.80^{abcd}	9.51 ± 0.45^{a}
3	8.04 ± 0.26^{abcd}	8.01 ± 0.80^{abcd}	8.57 ± 0.58^{abc}
4	7.13 ± 0.34^{bcde}	7.59 ± 0.61^{bcde}	8.63 ± 0.33^{abc}
5	6.64 ± 0.52^{de}	7.08 ± 0.66^{bcde}	8.74 ± 0.23^{ab}
6	6.60 ± 0.84^{de}	6.81 ± 0.79^{cde}	8.73 ± 1.01^{ab}
Time (h)	**ΔE^*_{ab}**		
	80°C	**90°C**	**100°C**
0	0.00^{f}		
1	15.20 ± 3.18^{a}	15.00 ± 1.07^{a}	10.92 ±0.70^{abcde}
2	7.95 ± 0.96^{cde}	7.08 ± 1.22^{e}	6.94 ± 0.27^{e}
3	7.83 ± 2.79^{de}	9.82 ± 1.91^{bcde}	9.26 ± 1.18^{bcde}
4	10.19 ± 0.74^{bcde}	11.00 ± 0.81^{abcde}	9.16 ± 0.75^{bcde}
5	12.38 ± 1.32^{ab}	12.17 ± 1.55^{abc}	9.77 ± 0.50^{bcde}
6	12.18 ± 1.50^{abc}	12.12 ± 1.13^{abcd}	9.05 ± 0.41^{bcde}

Results are means of three independent replicates (n=3) ± standard deviation; values with different letters are significantly different to each other $p \leq 0.05$

3.3. *Effect of dehydration on infrared spectra and composition of house crickets*

The dominant compounds reported in untreated house crickets are water (52 %–79 %), protein (13 %–25 %), chitin (1.14 %–2.08 %) and crude fat (1.6 %–18 %), consisting of palmitic acid (~26 %), linoleic acid (~35 %), and oleic acid (~24 %) (Tzompa-Sosa et al., 2014; Ververis et al., 2022). The principal absorbance peak centres in the untreated house cricket FT-IR spectrum (Fig. 3) were identified (Table 4)

Table 3
Browning index for oven-dried crickets.

Time (h)	Browning Index*		
	80°C	90°C	100°C
0	22.82 ± 2.00^{f}		
1	15.90 ± 2.32^{g}	22.33 ± 4.15^{fg}	29.71 ± 1.40^{de}
2	23.21 ± 1.72^{ef}	31.82 ± 2.04^{d}	38.94 ± 2.07^{abc}
3	33.39 ± 2.46^{bcd}	36.23 ± 1.12^{abcd}	38.80 ± 1.63^{abc}
4	32.15 ± 0.64^{cd}	36.50 ± 2.18^{abcd}	38.73 ± 1.31^{abc}
5	32.73 ± 0.65^{bcd}	36.39 ± 1.47^{abcd}	40.53 ± 1.52^{a}
6	32.26 ± 2.10^{cd}	34.25 ± 3.03^{abcd}	39.22 ± 4.42^{ab}

Results are means of three independent replicates (n=3) ± standard deviation; values with different letters are significantly different to each other p ≤ 0.05

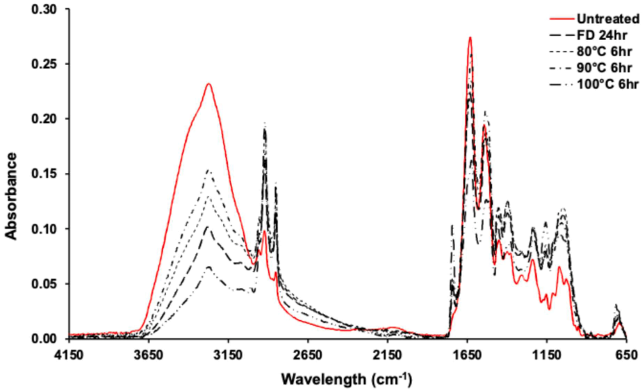

Fig. 3. ATR FT-IR spectra for untreated and dehydrated house crickets (n=3).

Table 4
Main infrared absorption peak centres and assignment in the FT- IR spectrum of ground untreated 5-week-old house crickets.

Main Absorbance Peak Centres (cm^{-1})	Possible Functional Group Contributors			
	Water (H_2O) (cm^{-1})	Protein ($RCH(NH_2)$-$COOH$) (cm^{-1})	α-Chitin ($(C_8H_{13}O_5N)_n$) (cm^{-1})	Lipids ($(CH3\ (CH2)_n$-$COOH)$) (cm^{-1})
3275	2800–3600 O—H symmetric stretch	Amide A 3070–3500 N—H symmetric stretch	3408–3433 O—H stretch 3103–3257 cm^{-1} N—H stretch	3300–2500 O—H symmetric/ asymmetric stretch
2923				2959–2872 C—H_3 symmetric/ asymmetric stretch
2852	2800–3600 O—H asymmetric stretch		2881 C—H stretch	2920–2830 C—H_2 symmetric/ asymmetric stretch
1738				1760–1690 C=O stretch
1633	1670 O—H—O scissor bend	Amide I 1600–1700 Major contributions C=O stretch Minor contributions C—N bend C—CN bend N—H bend	1643–1653 C=O stretch 1622 cm^{-1} C=O stretch	
1543		Amide II 1540–1570 C–N stretch N–H bend	1554–1563 N–H bend C–N stretch	
1454				1458 C—H_2 bend
1401			1412–1423 CH_2 ending, CH_3 deformation	1393–1417 C—H_2 bend
1240		Amide III 1200–1400 N—H bend C=O bend C—C stretch C—N stretch	1256 C—N stretch	1236 C—H bending C—O stretch
1177			1153 oxygen bridge stretch	1210–1160 C—C—O stretch
1074			1055–1066 C—O—C stretch	1100–1030 O—C—C stretch
702	700 O—H fingerprint	200–700 N—H wag		

Table 5
Data from the deconvolution of the Amide I peaks for freeze-dried crickets.

Time (h)	β-sheet (%)	α-helix/random coil (%)	β-turn (%)
0	46.46 ± 4.88	18.34 ± 3.41	22.18 ± 4.35
8	41.12 ± 1.43	19.89 ± 0.77	25.31 ± 1.30
16	40.73 ± 0.76	21.48 ± 1.01	24.28 ± 1.81
24	42.98 ± 5.46	20.97 ± 2.62	22.31 ± 3.01

Results are means of three independent replicates (n=3) ± standard deviation

and the contributing functional groups from these compounds assigned based on literature (Barth, 2007; Ibitoye et al., 2018; Lucarini et al., 2018; Ndiritu et al., 2023; Okwuosa et al., 2023; Palencia, 2018; Tatulian, 2013).

The Amide I absorbance area, which typically ranges between 1700–1620 cm^{-1}, is of particular interest when considering protein secondary structure. Any absorbances ≤1610 cm^{-1} are generally excluded as they are believed to be associated with carboxylate groups (COO-) and amide sidechain absorbances rather than secondary structure (Susi & Byler, 1986). The mean wavelength of the Amide I peak centre in the spectra of untreated crickets occurred at 1635 ± 2.5 cm^{-1}, indicating that the predominant protein structure may be β-sheet (Susi & Byler, 1986). There was no significant difference between control and freeze-dried crickets at any dehydration time point (Table 5), suggesting that native protein conformation is preserved during drying. The cuticle of insects has been shown to contain layers of chitin protected by a proteinaceous matrix (~50 %) made up of pleated β-sheet and β-turns (Finke, 2002; Iconomidou et al., 2001; Vincent, 2004; Willis et al., 2012). These proteins are cross-linked, and the matrix is stiff, hydrophobic, insoluble and chemically inert (Vincent, 2004). Powders containing particles of this may be unreactive and disruptive within a wider food matrix. Within the cricket, Hammer et al. (2023) reported that cricket muscle proteins are consistent with other meat sources: myosin heavy chain, paramyosin, actin, myosin light chain, tropomyosin 2 fragments, and tropomyosin 1 fragments. Proteins specific to the house cricket were also identified: heat shock protein 90, heat shock protein cognate 4, tubulin beta-1 and alpha-1, troponin T, arginine kinase, troponin I, apolipophorin-III, histone H2A, histone H3.3C, histone H2B, and histone H4 (Hammer et al. 2023). This is a complex blend of small and large proteins made up of β-sheet, α-helix, random coil and turns and bends. The proportions of these secondary structures were calculated for both untreated and freeze-dried house crickets and β-sheet is the dominant structure (Table 5). Pellerin and Doyen (2024) were the only other investigators identified to date who have reported secondary structural components for house cricket proteins following deconvolution of the Amide I peak. However, their study focused on alkaline extracted proteins, rather than whole crickets, and they reported calculated secondary structure data for the whole Amide I peak area of 1700–1600 cm^{-1}, making direct comparisons difficult.

By contrast, the FT-IR spectra for oven-dried crickets showed shifts in peak centres. The mean wavelength of the Amide I peak for cricket samples oven-dried for 6 h at 80°C, 90°C, and 100°C showed a significant reduction in wavelength (a red shift), during the first hour of heat application at all temperatures, and this remained constant during the minimum 6 h drying time (Table 6).

Peak shifts within the Amide I peak are typically attributed to protein conformational changes, but the heterogeneous nature of cricket powder introduces contributions from compounds other than protein, that might also influence this shift. Monosaccharides, such as glucose, absorb at 1644 cm^{-1} due to the stretching vibrations of their C=O bond, while their incorporation into Maillard reaction products shifts this to a slightly lower frequency (1641 cm^{-1}) (Zhang et al., 2019). Likewise, the disaccharide trehalose, has an absorption at ∼1680 cm^{-1} due to the bending peak of crystal water, which if removed may shift the overall peak to a lower frequency and the temperatures at which this occurs depends on the crystal structure (Raimi-Abraham et al., 2014). The increased removal of water in the oven-dried samples may have further reduced any vibrational contribution of the initial water O—H—O scissor bend, potentially increasing the intensity of lower frequency vibrations from β-sheet structures. The removal of a protein's water solvation shell could change tertiary structure or reduce hydrogen bonding between the C=O of the protein backbone and water, exposing binding sites on the outer face of the protein leading to intermolecular bonding (aggregation) with a lower absorbance frequency (∼1620 cm^{-1}). This could simply change vibrational frequencies and intensities from the secondary structure (Barth, 2007). The Amide II peak centre (typically between 1600–1500 cm^{-1}) affected by the vibrations from C–N stretching and N–H bending of the backbone, also shows a red shift to lower a lower frequency in oven-dried crickets during the first hour. This may also be indicative of a change in the bonding between proteins and the water solvation shell, and an increase in vibration of the N-H groups of the protein backbone as water is removed rather than an indication of any change in secondary structure (Barth, 2007).

Deconvolution of the oven-dried house cricket Amide I peaks showed no significant change in the underlying secondary structure of the proteins as a factor of dehydration time or temperature (Table 7). There are several factors that may potentially aid the stability of secondary protein structure in house crickets. The cross-linking and sclerotization of the proteins in the exoskeleton have been noted to infer structural stability (Vincent, 2004). A number of studies have identified that, depending on the intensity of thermal stress and the insect's physiological state, many insects upregulate cryoprotectants to mitigate the challenges of thermal stress and desiccation (King & MacRae, 2015; Mizrahi et al., 2010; Toxopeus & Sinclair, 2018), potentially decreasing uncontrolled protein denaturation and aggregation during fasting and freezing. We hypothese that these molecular chaperones could also stabilise protein secondary structure during oven-drying, but to date no study has been found to support this. Trehalose has been reported as being present in the haemolymph of house crickets (Wang & Patton, 1969) and is reported to work as a universal protein stabilizer (Kaushik & Bhat, 2003). Rapid cold hardening, potentially similar to that experienced during euthanasia, is reported to increase cryoprotectant synthesis in some species (Teets et al., 2020) and up-regulation of trehalose in crickets has been confirmed in a study on acclimatation (Toxopeus et al., 2019).

Table 6

Consolidated wavelength values for Amide I peak centre for oven-dried crickets.

Time (h)	Wavelength (cm^{-1}) 80°C	 90°C	 100°C
0	1635 ± 3.00^{a}		
1	1626 ± 0.76^{b}	1625 ± 1.00^{b}	1625 ± 1.15^{b}
2	1626 ± 0.87^{b}	1625 ± 0.58^{b}	1626 ± 0.50^{b}
3	1626 ± 0.58^{b}	1626 ± 1.15^{b}	1625 ± 1.26^{b}
4	1627 ± 0.50^{b}	1627 ± 0.58^{b}	1625 ± 0.58^{b}
5	1626 ± 0.29^{b}	1626 ± 0.29^{b}	1626 ± 0.29^{b}
6	1626 ± 0.58^{b}	1626 ± 0.58^{b}	1626 ± 0.58^{b}

Results are means of three independent replicates (n=3) ± standard deviation; values with different letters are significantly different to each other $p \leq 0.05$

Table 7

Data from the deconvolution of the Amide I peaks for oven-dried crickets.

Temperature (°C)	Time (h)	β-sheet (%)	α-helix/unordered (%)	Turns & bends (%)
Untreated	0	46.46 ± 4.88	18.34 ± 3.41	22.18 ± 4.35
80	1	47.40 ± 4.78	17.87 ± 1.16	22.43 ± 5.41
80	2	51.15 ± 0.98	14.68 ± 3.85	18.66 ± 3.35
80	3	47.61 ± 5.17	16.81 ± 2.34	22.67 ± 3.41
80	4	48.62 ± 3.92	16.88 ± 1.06	19.82 ± 3.33
80	5	46.41 ± 0.97	17.76 ± 1.28	21.51 ± 1.29
80	6	44.83 ± 7.84	19.57 ± 8.60	21.58 ± 0.56
90	1	47.15 ± 2.61	14.66 ± 4.17	23.37 ± 3.18
90	2	46.55 ± 2.77	14.27 ± 2.06	22.86 ± 2.28
90	3	51.74 ± 4.88	13.84 ± 4.20	23.96 ± 3.58
90	4	48.36 ± 1.61	14.15 ± 1.71	22.13 ± 2.42
90	5	46.43 ± 2.77	15.32 ± 2.90	22.50 ± 1.03
90	6	47.92 ± 3.97	15.42 ± 3.95	21.83 ± 3.28
100	1	49.38 ± 2.01	14.90 ± 1.59	20.62 ± 0.63
100	2	45.56 ± 1.91	15.33 ± 3.17	23.85 ± 1.17
100	3	48.96 ± 3.09	13.49 ± 2.80	23.67 ± 2.68
100	4	45.08 ± 4.68	15.47 ± 3.77	24.86 ± 1.32
100	5	47.90 ± 2.11	14.34 ± 3.34	23.95 ± 1.25
100	6	46.80 ± 1.84	17.38 ± 1.58	22.07 ± 1.89

Results are means of three independent replicates (n=3) ± standard deviation

Other peaks that appeared to shift during oven-drying were those where contributions from lipids may have been influential. Hutchins and Martin (1967) profiled the lipids in house crickets reporting the presence of high levels of triacyglycerols and free fatty acids together with other lipid classes such as diglycerides, monoglycerides, phospholipids and sterols. Okwuosa et al. (2023) identified lipid classes in black soldier fly by FT-IR and have associated the infra-red spectra to functional groups. Applying their assignments to the peak centre values in the untreated cricket spectra in this study, contributions of the lipid classes to the peaks can be allocated (Table 8).

Given the complexity of the house cricket powder, it is difficult to connect any change directly to lipid oxidation. For example, the small peak identified originally at 1738 cm^{-1} coincides with a blue shift to a

Table 8

Assignment of lipid fractions based on FT-IR functional group absorptions.

Untreated Peak Centre (cm^{-1})	Mean Peak Centres after 6 h oven-drying (cm^{-1})	Functional Group	Lipid Class
3275	3274	O-H stretching vibration	Carboxylic acids and esters
2922	2920	CH_2 and CH_3 symmetric and asymmetric stretching	TAG, DG, MG
2852	2852	O-H CH_2 and CH_3 symmetric and asymmetric stretching	FFA TAG, DG, MG
1738	1743	C=O	FFA TAG, DG, MG
1401	1400	CH_2 bend	Glycerol group of TAG, DG, MG
1240	1235	C-O	FFA
1163	1158	C-C-O	TAG, DG, MG
1074	1067	O-C-C	TAG, DG, MG
702	708	CH_2 rock	TAG, DG

Key: triglycerides (TAG) free fatty acids (FFA), diglycerides (DG) and monoglycerides (MG) higher wavelength. This may simply be indicative of the removal of water concentrating the absorbance contributions from triacylglycerides, free fatty acids and glycerols or could be a mix of such events with additional contributions from lipid oxidation such as the formation of fatty acids, aldehydes and ketones (Rohman & and Che Man, 2013).

3.4. *Effect of dehydration on the thermal stability of house cricket powder*

Thermogravimetric (TGA) and derivative thermogravimetric (DTG) curves for the untreated and dehydrated crickets were prepared to assess changes to the material mass of cricket powder as a function of temperature during heating (Supplementary Data Figures S1a and S1b).

Mass losses were observed for all treatments but followed a similar trajectory. The first mass loss is likely to be associated with adsorbed and strongly hydrogen bonded free water and occurs up to ~110°C. In each dehydrated powder, the loss is less than 10 % which is considered normal (Psarianos et al., 2022). The loss is significantly higher in untreated crickets but is likely consistent with their higher initial water content (Ververis et al., 2022). Analysis of the DTG curves indicated a minimum of three other mass losses in all samples, with onset of initial decomposition commencing at ~151–169°C and the mass loss peaks (DTG_{max}) occurring at ~201–213°C, ~321–325°C, and ~353–373°C respectively.

None of the peaks returned to baseline, suggesting that irreversible decomposition of the powders progresses as temperature rises. Given that cricket powder is heterogeneous in nature, a number of macromolecules could be contributing to each peak seen on the DTG curve. Bogusz et al. (2024) assessed the thermal stability of powders from yellow mealworm and report that the second peak at 240°C was likely to be due to breaking of intermolecular hydrogen bonds in proteins. This observation further supports our earlier FT-IR deconvolution findings, indicating the cricket protein secondary structure predominantly remains stable during dehydration. After dehydration, any structural change appears to require higher temperatures with onset occurring ~151–169°C (peaking ~201–213°C). Alves et al. (2022) carried out gravimetric analysis of model pure fatty acids and fatty acid methyl esters (FAMEs), reporting onset and final degradation temperatures (DTG_{max} equivalent) of 139°C and 294°C for oleic acid, 118°C and 266°C for palmitic acid, and 143°C and 336°C for FAMEs, respectively. Cricket powder contains these fatty acids and their degradation could be contributing to mass losses seen in the DTG curve within several peaks, and may also explain the early mass loss in powder dried at 90°C. Mohan et al. (2020) reported that decomposition of chitin extracted from different insect orders ranged 307–412°C; our DTG curve has two peaks that fall within this range. Moussout (2016) suggested that this loss is likely due to depolymerisation or decomposition of the polymer chains and cleavage of glycosidic bonds in chitin.

3.5. *Effect of dehydration on house cricket volatile compounds*

To the best of the authors' knowledge, this is the first report on the volatile compounds in raw untreated house crickets. The full table of data for all the volatile compounds identified (>80) in the headspace of untreated cricket samples can be found in Table S1 in the supplementary material. FAMEs were the major compound class identified (29 in total) making up 72 % of the volatile compounds in the headspace. Compounds such as methyl hexadecanoate, methyl tetradecanoate, methyl dodecanoate, methyl hexanoate, methyl octanoate, methyl acetate and methyl (z)-octadec-9-enoate made up 59 % of this compound class. Similar FAMEs were reported by Hutchins and Martin (1967) in the lipidome of the house cricket, although in different percentages, and McFarlane (1968) suggested they are present in the cuticle. Parker (2015) suggested that the most prevalent FAMEs are long-chain and more likely to contribute a fatty, waxy aroma, which is supported in findings by Luebke (2021) where the aroma of FAMEs (seven of which were identified in this study) exhibited waxy, fruity and fatty notes.

Carboxylic acids were also identified in the headspace of the samples and made up 16 % of the total volatile compounds identified, with acetic acid, 3-methylbutanoic acid, hexanoic acid, and propanoic acid being the most abundant. These compounds were identified by McFarlane et al. (1983) in the brown fluid that accompanied defecation and Tzompa-Sosa et al. (2019) reported the presence of acetic acid and propanoic acid anhydride odorants following an aqueous extraction of cricket oils from whole frozen house crickets. These short-chain fatty acids are reported to impart a sour, cheesy, sweaty, sharp aroma (Luebke, 2021) and to have low aroma thresholds, therefore are likely to be detected a very low concentration. However, Perez-Santaescolastica et al. (2022) suggested that the aromatic contribution of this group is mainly undesirable, being described as rotten, faecal or pungent.

The remaining 12 % of total volatiles was made up of alkanes, alcohols, aldehydes, nitriles, sulphur compounds, terpenes and individual compounds from other classes, many of these can be formed through fatty acid metabolism pathways involving enzymes. Specifically, it should be noted that aldehydes are character impact compounds strongly influencing aroma or flavour in foods, sulphur compounds can be pungent and objectionable nitrogen-containing compounds, whereas terpenes also contribute to aroma (Parker, 2015).

This is the first study to assess changes in the volatile profile of house crickets as a factor of dehydration time during freeze-drying. There was a general trend of increasing volatile concentrations as dehydration proceeded; seventeen new compounds were identified, and some deodorisation appeared to occur during extended dehydration times. FAMEs were again the most abundant compounds in the headspace, making up 88 % of the total volatile profile respectively, with significant increases in concentration at the respective time points for most. Similar compounds were identified by Khatun et al. (2021) in 40 h freeze-dried samples. Methyl non-3enoate is the exception to this, with an initial significant increase in concentration at 8 h but a return to levels similar to untreated crickets at 24 h.

All carboxylic acids, with one exception (nonanoic acid), showed a significant increase in concentration as dehydration proceeds. Increased concentrations of carboxylic acids, with sweaty, cheesy aroma profiles, may impact perceptions of the powder and introduce potential off flavours to food matrices. Sensory evaluation of freeze-dried powders is recommended to confirm this and if confirmed formulating to trap these in the broader food matrix may be essential to limit their impact on final product flavour (Piornos et al., 2019).

Compounds that appeared after 8 h of freeze-drying included an alcohol, aldehydes, fatty acid ethyl esters, two ketones and a lactate ester. This is the first study that reports ethyl esters in the house cricket, however ethyl esters have been reported in other insects (Perez-Santaescolastica et al., 2022; Perez-Santaescolastica et al., 2023). The crickets used in the current study were not fast frozen, and this may have affected ice crystal size potentially damaging cell structures, enabling the release of additional volatile compounds (Fellows, 2017).

Some minor deodorisation was apparent at extended drying times, but there is no consistent trend, and this may simply reflect sample heterogeneity rather than true deodorisation. Notably, in the alkane class, octane, hexane, and 3-methylundecane disappeared from the headspace compared to the control (untreated crickets), while others were reduced (dodecane by ~38 %, and undecane by ~64 %). Two of the terpenes also disappeared, and a third reduced in concentration. The removal of ethyl esters has been demonstrated during freeze-drying in other foods (Abouelenein et al., 2021; Huang et al., 2012; Kesler et al., 2023) and some ethyl esters in this study exhibited signs of minor deodorisation at 24 h. Ethyl esters are absent in the study by Khatun et al. (2021), and from the evidence presented here, it could be suggested that extended drying periods may lead to their complete removal.

The highest number of volatile compounds were identified in the headspace of oven-dried samples. FAMEs were the most abundant compounds, however, with the exception of three compounds, their concentration was not significantly different to the untreated crickets at any time point. Khatun et al. (2021) suggested that esters degrade during oven-drying. It is feasible that a change in overall pH during dehydration could catalyse the hydrolysis of the methyl esters, forming carboxylic acids and alcohol, and although no significant changes to the original carboxylic acid concentrations were seen at any time point, two additional carboxylic acids were revealed. Concentrations of decanoic acid and dodecanoic acid appear to be temperature dependent with the highest quantities observed in the samples dried at 80 °C and 90 °C. These findings suggest that careful control of processing temperatures could be required to limit the introduction of off-flavours from dried cricket powder within a food matrix, or that the introduction of a defatting step may be essential to reduce any undesirable off-flavours.

Thirty-five new compounds were formed during oven-drying attributable to Strecker degradation, Maillard and lipid oxidation reactions. They appeared in the samples at 3 h at 80 °C and 90 °C, and at 1 h at 100 °C, and continued to increase as dehydration proceeded. These compounds were reported to be produced by degradation of valine, isoleucine, leucine and alanine in low moisture environments (Parker, 2015; Rainer Cremer & Eichner, 2000). They exhibit pleasant malty, chocolate, coffee, nutty aromas, but possibly a less pleasant musty aroma (Luebke, 2021). Strecker degradation can also trigger a chain reaction that yields sulphur compounds. The reaction of methionine can produce 3-methylsulfanylpropanal (methional), which degrades to methanethiol, that oxidises to (methyldisulfanyl) methane. All of these compounds, found in the oven-dried samples, tend to have low odour thresholds (Parker, 2015; Zhang et al., 2023) and are reported to impart meaty, sulphurous, onion, cabbage-like, eggy aromas (Luebke, 2021), that may be perceived as unpleasant depending on the application of the powder.

The final stages of the Maillard reaction yield pyrazines, pyrroles, pyridines and sulphur compounds, which were also present in oven-dried cricket samples, with their concentrations increasing as function of time, temperature and decreasing a_W. Although it is not possible to confirm the formation pathways of the compounds identified in the house cricket powders, the presence of free amino acids and reducing sugar precursors in the haemolymph have been reported (Adedeji et al., 2022; Collavo et al., 2002; Finke, 2002; Finke, 2007; Malla et al., 2022; Nakagaki et al., 1987; Nowosielski & Patton, 1965; Ritvanen et al., 2020; Wang & Patton, 1969). In the case of pyrazine, 2-ethyl-6-methylpyrazine, 2,5-dimethylpyrazine, 2,6-dimethylpyrazine and 1H-pyrrole, model systems have shown that they can form even in the absence of a carbohydrate source (Shu, 1999; Yaylayan & Keyhani, 2001). Pyrazines and pyrroles are reported to impart pleasant roasted, nutty, meaty/beefy, cocoa aromas, but possibly a less pleasant musty aroma (Luebke, 2021).

Finally, oven-dried powders contained compounds that could be the result of lipid oxidation. Tzompa-Sosa et al. (2014) identified the dominant lipids of the house cricket as palmitic acid, oleic acid, linoleic acid and stearic acid. Aldehydes (hexanal, octanal, (*E*)-2-heptenal (2*E*, 4*Z*)-deca-2,4-dienal), ketones (octan-2-one, nonan-2-one and decan-2-one and heptan-2-one, undecane-2-one) and alcohols (1-octen-3-ol, octan-1-ol, phenylmethanol), have been associated with oxidation of these lipids (Domínguez et al., 2019; Han et al., 2023; Zhou et al., 2025). Lipid oxidation products can also initiate degradation of amino acids (Hidalgo and Zamora (2019). All these compounds are present in the oven-dried powders, and their concentrations increase significantly with longer drying times at higher temperatures.

To visualise the differences in the volatile profile of house crickets between the dehydration techniques, principal component analysis was used (Fig. 4). The first two principal components accounted for 86 % of the variation in the data. It can be clearly seen that the dehydration techniques were separated across PC1 and dehydration temperature and time across PC2. The dominant volatile compounds associated with these differences are FAMEs and non-enzymatic browning products.

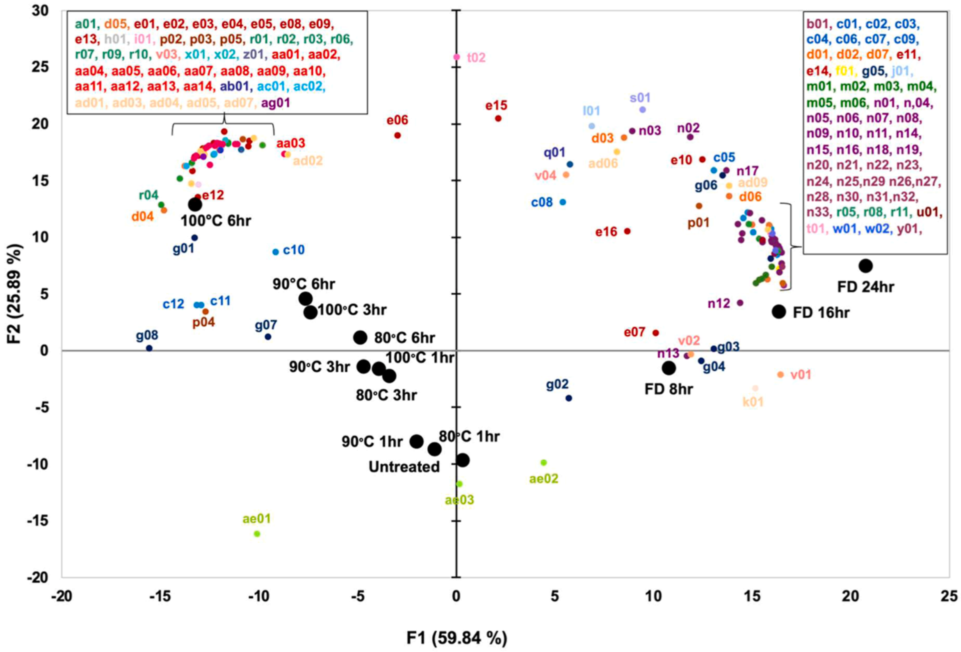

Fig. 4. Principal component biplot of dehydration techniques applied to house crickets (● active observations n=3; ● active variables).
Volatile Compound Class Abbreviation Key: a = acetamide, b = acetate, c = carboxylic acid, d = alcohol, e = aldehyde, f = alkadiene, g = alkane, h = amide, i = benzaldehyde, j = benzene, k = cumene, l = cyclooctane, m = fatty acid ethyl ester, n = fatty acid methyl ester, p = furan, q = indole, r = ketone, s = lactate ester, t = lactone, u = nicotinic acid, v = nitrile, w = phenol, x = phenylacetaldehyde, y = polycyclic aromatic hydrocarbon, z = pyranone, aa = pyrazine, ab = pyridine, ac = pyrrole, ad = sulfur compounds, ae = terpene, af = xylene, ag = γ-lactam.

4. Conclusion

The dehydration parameters established for EU approved house cricket powders and used as a guide in this study, produced a cricket powder sufficiently dried to achieve microbial stability. No significant changes in moisture content and water activity were observed during oven-drying for longer than 3 h at any temperature, indicating that from a processing point of view, high temperature and relatively short drying times could be effective.

Colour changes were observed in both dehydration methods. The reoxygenation of metalloproteins during the application of freeze-dried cricket powders in food formulations could affect colour properties, as could the colour changes in oven-dried cricket powders, potentially attributable to melanoidin formation, which are irreversible. Deconvolution of the Amide I peak of dehydrated samples showed no difference in protein secondary structure regardless of treatment, but the increased moisture removal in oven-dried crickets indicated peak changes that are likely related to intra- and intermolecular effects on vibrational frequencies. With regards to volatile compounds in dehydrated cricket powders, increased concentration of baseline volatile compounds and appearance of new cricket-related compounds were observed during freeze-drying over time. In contrast, oven-drying lead to volatile compound development, as a result of Maillard, Strecker degradation and lipid oxidation reactions.

In conclusion, dehydration has been shown to introduce changes in the physical attributes of cricket powders. This information could be used to identify modifications to powder manufacturing procedures to achieve an optimal product, inform food reformulation strategies, including masking of potential off flavours if identified by sensory characterisation, and aid the extraction of cricket powder macromolecules for use as ingredients in food applications.

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Ethical statement - studies in humans and animals

No human or animal studies were conducted in this work.

CRediT authorship contribution statement

Susan Rudlin: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Stella Lignou:** Writing – review & editing, Supervision, Software, Methodology, Conceptualization. **Ruan Elliott:** Writing – review & editing, Supervision. **Geoffrey Knott:** Supervision, Resources, Conceptualization. **Afroditi Chatzifragkou:** Writing – review & editing, Supervision, Methodology, Funding acquisition, 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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.afres.2026.101860.

Data availability

Data will be made available on request.

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