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RESEARCH ARTICLE

Comparative analysis of drying technologies for black soldier fly (*Hermetia illucens*) larvae: multidimensional assessment

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Abstract

This study explores the impact of five drying technologies – sun drying (SD), hybrid solar-electric drying (HSED), vacuum freeze drying (VFD), greenhouse drying (GD), and microwave drying (MD) – on the quality of black soldier fly larvae (BSFL). Key parameters, including yield, specific energy consumption, drying rate, and various nutritional, physicochemical, techno-functional, structural, and thermal properties, were analysed for each method. VFD, while being the most effective at preserving nutrients and structure with a yield of 37.5%, required high energy (206.86 kWh/kg) and extended drying times (72 h), limiting its scalability. Conversely, HSED, with a lower energy consumption (1.62 kWh/kg) and shorter drying time (6 h), offered a sustainable balance of efficiency and product quality suitable for large-scale use. In contrast, GD resulted in the highest nutrient losses and structural degradation. The findings guide the selection of effective and sustainable drying methods for producing high-quality BSFL for food and feed applications.

Keywords

drying technologies – insect – nutritional preservation – product quality – sustainable processing

1 Introduction

Insects are increasingly recognized as a promising and sustainable food and feed source. They have long been part of human diets, with over 2000 identified edible species offering a combination of nutritional, economic, and environmental benefits (Anusha and Negi, 2023). They are rich in protein, fat, and chitin, as well as micronutrients like minerals and vitamins, making them nutritionally comparable to fish, meat, and soy while being more sustainable, affordable and locally sourced (Bessa *et al.*, 2020). Economically, insect farming requires low investment and minimal infrastructure and resources, creating potential income opportunities (Kour *et al.*, 2024; van Huis and Oonincx, 2017). Environmentally, compared to traditional livestock produc-

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tion, insect farming has a smaller ecological footprint, as insects are more efficient in converting feed into protein, require significantly less water, energy, and land, and generate over 100 times lower greenhouse gas emissions (Cadinu *et al.*, 2020; Oonincx *et al.*, 2010).

Among the various edible insects, black soldier fly larvae (BSFL, *Hermetia illucens*) have garnered considerable attention due to their nutritional profile and versatility. BSFL are widely farmed as an alternative protein source due to their rapid growth rate and exceptional ability to efficiently bioconvert organic waste streams into high-quality nutrients, making them a promising and sustainable protein source that aligns with circular economy principles (Hoffmans *et al.*, 2024; Peguero *et al.*, 2022). They are rich in protein, with levels ranging from 30-53% of dry matter, and contain a well-balanced composition of essential amino acids, healthy fats, chitin, minerals, and other nutrients (Bessa *et al.*, 2020). As a result, BSFL have been applied in various industries, including animal feed, aquaculture, pet food, organic fertilizers, biodiesel production, and cosmetics (Siddiqui *et al.*, 2024).

BSFL have a high initial moisture content, typically above 60%, which necessitates drying as a critical post-harvest processing step to enhance their shelf life, safety, and stability during storage and transportation, as well as to facilitate their integration into food and feed (Parniakov *et al.*, 2022; Shorstkii *et al.*, 2022). However, the choice of drying method plays a crucial role in determining the quality of the larvae, the energy efficiency of the process, and its environmental impact. Therefore, selecting a method that optimizes product quality while ensuring efficiency and sustainability is essential (Parniakov *et al.*, 2022).

Various drying methods, from traditional sun drying to advanced techniques like freeze drying, spray drying, and microwave-assisted drying, have been investigated for BSFL. Lehmad *et al.* (2024a) reported that forced-air oven drying of BSFL at temperatures ranging from 40 °C to 70 °C yielded high protein content (39.67-45.29%). However, the overall quality of the larvae decreased at higher drying temperatures, indicating potential nutrient degradation. Huang *et al.* (2019) conducted a comparison between microwave drying (15 min at 500 W) and oven drying (at 60 °C) for producing BSFL flour. Their findings indicated that while the protein content and quality were similar for both methods, protein digestibility was significantly higher – exceeding 75% – when the larvae were dried using the oven method compared to microwave drying. Pornsuwan *et al.* (2023) investigated the effects of different drying methods on the physical and chemical properties of BSFL. The study found that while all methods preserved the nutritional value, microwave and hot-air oven drying were more effective at retaining higher nutrient levels and enhancing physical properties compared to the parabola dome method. The parabolic dome is widely used for drying large quantities of fruits and vegetables, making it an efficient and well-suited option for these products. Its design offers high suitability and performance for this purpose (Kreetachat *et al.*, 2023). For drying BSFL, the lower performance of the parabola dome was attributed to its reliance on passive solar energy, which results in longer drying durations (up to 48 h) and less consistent temperature control. These conditions can promote oxidation and structural degradation, thereby reducing the nutritional and functional quality of the dried larvae (Pornsuwan *et al.*, 2023). Monisha and Loganathan (2021) studied the effects of freeze-drying and direct solar drying on the quality of defatted BSFL flour. The findings showed that freeze-drying produced flour with a higher protein content (44.63%) and better storage stability compared to solar-dried flour (39.74%), highlighting its potential as a functional ingredient. However, the higher cost of freeze-drying limits its practicality for industrial-scale use compared to the more economical solar drying method. Purnamasari *et al.* (2020) examined how different growth media (fruit pulp, cassava peel, food scraps, tofu waste), drying temperatures (55, 65 and 75 °C), and drying durations (24 h and 36 h) affected the nutritional composition of BSFL using an oven dryer. Their study found that BSFL reared on tofu waste exhibited the highest protein content (up to 50.65%), particularly when dried at 55 °C for 24 h. This suggests that both the nutritional quality of the rearing substrate and the drying parameters can significantly influence the final protein content of the larvae. Saucier *et al.* (2021) compared the effects of forced convection drying at 60 °C and freeze-drying on the quality of BSFL. The study found that hot-air drying was up to six times faster and resulted in a higher protein content (40.0%) compared to freeze-drying (38.5%). However, hot-air drying caused greater colour change and higher oxidation levels, while freeze-drying better preserved the larvae's appearance and stability. Zulkifli *et al.* (2022) studied the impact of oven drying and spray drying on the nutritional quality of BSFL. The results showed that while both methods retained essential nutrients such as amino acids, fatty acids, minerals, nucleotides, and vitamins, spray drying was more effective at preserving the overall nutritional value of the larvae. Lehmad *et al.* (2024b) explored the use of hybrid solar-electrical drying for BSFL and found it to be environmentally and economically beneficial, with a short payback period of 0.71 years and CO_2 emissions of 72.58 kg/year, along with a net CO_2 mitigation of 57.19 tons over its lifespan. The dried larvae had a high protein content ranging from 38.14% to 42.33%, exceeding the 34% industry standard and outperforming conventional drying methods in quality.

Our bibliographic review and current knowledge reveal a clear research gap in comprehensively analysing the impact of different drying methods on BSFL across multiple dimensions. This study aims to investigate and compare sun drying, hybrid solar-electric drying, vacuum freeze drying, greenhouse drying, and microwave drying in terms of energy consumption, as well as their effects on the nutritional, physicochemical, thermal, structural, and techno-functional properties of BSFL. The objective is to identify the most effective method for industrial-scale production that produces a high-quality product meeting market standards, while ensuring eco-friendly, cost-effective, and energy-efficient production practices.

2 Materials and methods

To maintain experimental consistency, the BSFL were reared exclusively on commercial chicken feed until they reached 13 days of age. This feed contained a minimum of 19.5% crude protein, 2% crude fat, 0.7% phosphorus, and 1% calcium, with maximum levels of 6% minerals, 5% crude fiber, and 13% moisture. It also included vitamins A (10^6 IU/100 kg), D (150 000 IU/100 kg), and E (2000 IU/100 kg), along with 10 mg/kg of avilamycin. After a 24 h fasting period, the larvae were washed, drained, and euthanized by blanching in boiling water for at least 40 s. Following blanching, they were stored in a freezer at –20 °C until further use. The rearing and harvesting followed the insect welfare standards set by the International Platform of Insects for Food and Feed (IPIFF, 2024). The initial moisture content of the larvae was 65.00 ± 0.97% (wet basis). The experimental methodology is illustrated with a schematic diagram in Figure 1, which provides enhanced visual clarity.

Drying technologies

The BSFL were thawed overnight in the refrigerator before undergoing the drying process. Five different drying technologies – sun drying (SD), hybrid-solar-electric drying (HSED), vacuum freeze-drying (VFD), greenhouse drying (GD), and microwave drying (MD) – were employed to reduce the moisture content of the larvae to below 8%. These methods were selected to represent a broad range of drying strategies, from low-cost, energy-efficient systems (SD, GD, HSED) commonly used in small-scale or rural contexts, to advanced, high-efficiency technologies (MD, VFD) used in industrial and laboratory settings. This selection enables a comprehensive comparison across traditional and modern approaches in terms of energy demand, processing time, and impact on product quality. All drying experiments were performed in triplicate to ensure reliability and accuracy of the results.

Sun drying (SD): A 500 g batch of BSFL was evenly spread in a thin layer on stainless steel trays measuring 0.95 × 1 m and dried under direct sunlight from 9 AM to 6 PM each day. At the end of each drying session, the samples were stored in airtight zip-lock bags, and SD continued the following day until a constant weight was achieved. During drying, average environmental conditions were as follows: ambient temperature of 31 ± 2 °C, relative humidity of 27 ± 4%, wind velocity of 4.17 ± 0.2 m/s, and solar radiation of 520 ± 10 W/m^2. Moisture content was monitored at 2 h intervals to track progress until stabilization. The final moisture content of the samples reached 7.87 ± 0.09% (wet basis).

Hybrid solar-electric drying (HSED): A 500 g batch of BSFL was dried using a HSED under non-controlled natural ventilation conditions. Details of the HSED system are provided by Lehmad *et al.* (2024b). The average drying conditions were as follows: chamber temperature of 60 °C, chamber relative humidity of 15 ± 4%, ambient temperature of 30 ± 2 °C, ambient relative humidity of 25 ± 4%, wind velocity of 2.78 ± 0.2 m/s, and solar radiation of 680 ± 10 W/m^2. Moisture content in the samples was monitored at intervals of 10 to 30 min throughout the drying process until a stable weight was achieved. The final moisture content was recorded at 6.21 ± 0.08% on a wet basis.

Vacuum freeze-drying (VFD): The vacuum freeze-dried BSFL was prepared by evenly spreading 500 g of larvae across three stainless steel plates and drying them for 72 h using a freeze dryer (Bio base BK-FD12P, Biobase, Shandong, P.R. China). The pre-freezing temperature was set at –20 °C, with a condenser temperature of –60 °C, a heating plate temperature of 25 °C, and a chamber pressure of 10 Pa. The moisture content of the samples was monitored at 2 h intervals throughout the process until a stable weight was achieved. The final moisture content of the sample was determined to be 3.61 ± 0.03% on a wet basis.

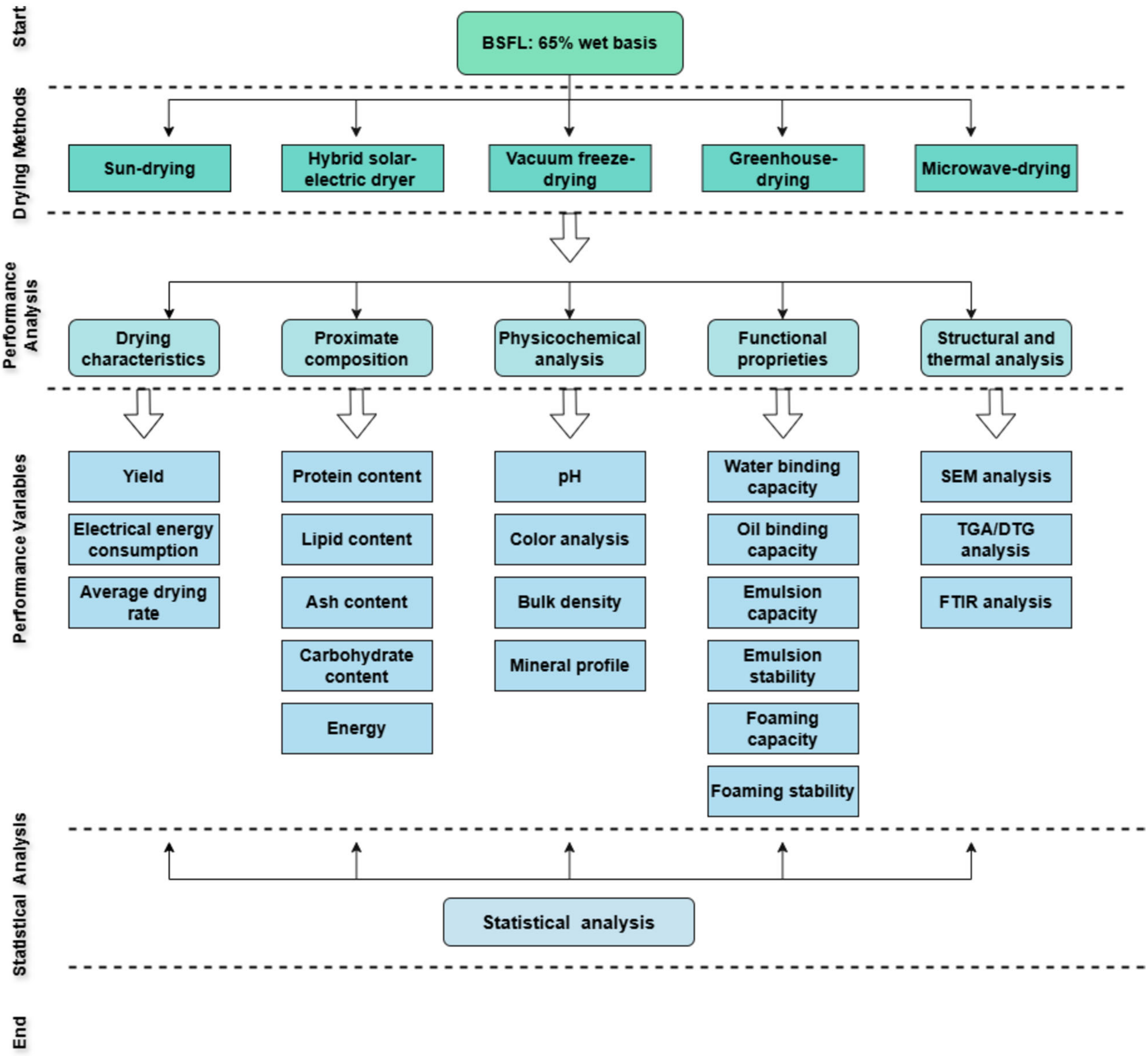

FIGURE 1 Visual overview of the experimental methodology.

Greenhouse drying (GD): A 500 g batch of BSFL was divided into two portions and spread in a thin layer within a greenhouse chamber measuring 1 × 0.8 × 0.5 m, utilizing natural convection for drying. The process was conducted daily from 11 AM to 6 PM, with an average chamber temperature of 63 ± 2 °C and relative humidity of 11 ± 4%. Average ambient conditions included a temperature of 35 ± 2 °C, relative humidity of 20 ± 4%, wind velocity of 3.61 ± 0.2 m/s, and solar radiation of 610 ± 10 W/m^2. Moisture content was monitored at intervals of 10 to 30 min to ensure consistent drying until a stable weight was reached. The final moisture content was recorded at 5.91 ± 0.07% on a wet basis.

Microwave drying (MD): Samples (500 g) were divided into five portions and evenly spread onto a glass plate positioned at the center of a turntable inside the microwave cavity. The larvae were dried using a 600 W microwave oven (MWD319/119) until they reached a constant weight. The moisture content of the samples was monitored at 1 min intervals throughout the drying process to ensure complete drying. The final moisture content of the sample was determined to be 7.07 ± 0.09% on a wet basis.

Drying time, yields, specific electrical energy consumption (*SEEC*), *and average drying rate* (*ADR*)

Yield: The yield was determined by measuring the change in sample weight before (M_1) and after the drying process (M_2), using the following formula as outlined by Hu *et al.* (2023).

$$\text{Yield}(\%) = \frac{M_2}{M_1} \times 100\% \quad (1)$$

Specific electrical energy consumption (SEEC): The electrical energy consumption for drying BSFL was calculated using equations (2) and (3) (Hadibi *et al.*, 2023):

$$\text{SEEC} = \frac{E}{M_{\text{evp}}} \quad (2)$$

$$M_{\text{evp}} = \frac{(X_{\text{i}} - X_{\text{f}})}{(100 - X_{\text{f}})} \times M_1 \quad (3)$$

In this context, SEEC represents the specific electrical energy consumption (kWh/kg), E denotes the total electrical energy consumption measured from an electric meter (kWh), and M_{evp} refers to the amount of moisture evaporated during the drying process (kg). The final moisture content (X_{f}) after drying was reduced to less than 8% (wet basis), starting with an initial batch mass (M_1) of 0.5 kg of BSFL, which had an initial moisture content (X_{i}) of 65 ± 0.97% (wet basis).

Average drying rate: The average drying rate (ADR) was calculated following the methodology outlined by Lehmad *et al.* (2024a). This approach involves measuring the amount of water removed per unit of dry matter over a specified time period, expressed in kg of water per kg of dry matter per h (kg water/kg (dm · h)).

Proximate composition analysis

The analyses were conducted following the standard protocols established by the Association of Official Analytical Chemists (AOAC, 1999). Moisture content was measured using a convection oven (AX 30, Carbolite Gero, Germany) at 105 °C for 24 h, as per AOAC 950.46. For ash content, the AOAC 942.05 method was employed, with a muffle furnace (Thermolyne Furnace, Type 30400, USA) set at 600 °C for 2 h. Protein content was determined using the Kjeldahl method (AOAC 984.13), calculated with a nitrogen-to-protein conversion factor of 4.76. This value was used instead of the conventional 6.25 to provide a more accurate estimate of true protein content, as insects like *Hermetia illucens* contain significant amounts of non-protein nitrogen sources, such as chitin and nucleic acids (Janssen *et al.*, 2017). Fat content was determined using the Soxhlet apparatus with n-hexane, following AOAC 920.39. Carbohydrates were derived by subtracting the combined values of moisture, protein, fat, and ash from the total mass, and energy values were calculated as follows:

$$\text{Energy}\left(\frac{\text{kcal}}{100\text{ g}}\right) = 4(\%\text{ Carbohydrate} + \%\text{ Protein}) + (9\% \times \%\text{ fat}) \quad (4)$$

Physicochemical analysis

pH measurement: To measure pH, 1 g of finely ground sample was mixed with 9 ml of distilled water and homogenized for 30 s. The pH meter (CRISON micro pH 2000, Spain) was calibrated prior to use with standard buffer solutions at pH 4, 7, and 9 to ensure accurate readings.

Colour measurement: A colorimeter (CR-400, Konica Minolta, Osaka, Japan) was used to assess the L^* (lightness), a^* (redness), and b^* (yellowness) values of both fresh and ground dried samples, with measurements taken using a white calibrated plate, D65 illuminant, and a 10° standard observer. The CIE Lab* values of fresh larvae were used as the reference. Changes in colour, including ΔE (colour difference), chroma (C^*), hue angle (h^*), and the browning index (BI) were calculated using the following equations:

$$\Delta E = \sqrt{\left(L_0^* - L_{\text{d}}^*\right)^2 + \left(a_0^* - a_{\text{d}}^*\right)^2 + \left(b_0^* - b_{\text{d}}^*\right)^2} \quad (5)$$

The subscripts 0 and d represent the measured values of the larvae in their fresh and dried states, respectively.

$$C^* = \sqrt{a^{*2} + b^{*2}} \quad (6)$$

$$h^* = \tan^{-1}\left(\frac{b^*}{a^*}\right) \quad (7)$$

$$\text{BI} = \frac{(100 \times (x - 0.31))}{0.172} \quad (8)$$

where:

$$x = \frac{a^* + (1.75 \times L^*)}{(5.645 \times L^*) + a^* - (0.3012 \times b^*)} \quad (9)$$

Bulk density: To measure the bulk density of the dried samples, 5 g of BSFL meal were weighed and placed into a 25 ml graduated centrifuge tube that had been previously weighed (this weight was recorded as W_1). The tube was then gently tapped on the laboratory bench several times to allow the powder to settle and reduce air gaps, until the volume no longer decreased. The final volume of the compacted powder was recorded (V_1, in ml), and the tube was weighed again (W_2). The bulk density (g/ml) was calculated by subtracting the initial weight of the empty tube (W_1) from the final weight (W_2), and dividing the result by the settled volume (V_1), as shown below:

$$\text{Bulk density (BD)} = \frac{W_2 - W_1}{V_1} \tag{10}$$

Mineral profile: The determination of minerals was performed using the wet ashing technique, adhering to the methodology described by Akinyele and Shokunbi (2015). The concentrations of copper (Cu), magnesium (Mg), zinc (Zn), manganese (Mn), and iron (Fe) were analysed with an atomic absorption spectrophotometer (AA-7000, Shimadzu, Japan) utilizing an air/acetylene flame. Meanwhile, the levels of sodium (Na), calcium (Ca), and potassium (K) were evaluated using flame emission spectroscopy (PFP7 flame photometer, Jenway, UK).

Techno-functional properties

Water binding capacity and oil binding capacity: The water binding capacity (WBC) was evaluated following the method outlined by Bessa *et al.* (2022), with some minor adjustments. A 1 g sample of BSFL was mixed with 10 ml of distilled water in a pre-weighed 15 ml graduated centrifuge tube and vortexed for 5 min. The mixture was then centrifuged (Universal 320 R, Hettich, Tuttlingen, Germany) at 3220 × *g* for 10 min. After this, the supernatant was carefully poured off, and any remaining unbound water was eliminated by inverting the centrifuge tube onto an absorbent towel for 1 h. The WBC was represented as the percentage of retained water per gram of the sample and calculated using Eq. (11).

$$\text{WBC (\%)} = \frac{m_1 - m_0}{m_0} \times 100 \tag{11}$$

Here, m_0 and m_1 denote the initial and final weights of the sample, respectively.

To determine the oil binding capacity (OBC), 0.3 g of the sample was mixed with 3 ml of sunflower oil, following the method described by Bessa *et al.* (2022). The mixture was vortexed for 1 min and then allowed to rest at room temperature for 30 min to promote oil absorption. It was subsequently centrifuged at 3220 × *g* for 10 min. The supernatant was carefully discarded, and the tube was inverted on absorbent paper for 1 h to remove excess oil. OBC was calculated as the percentage of oil retained per gram of sample, using the same equation as for WBC (equation (11)).

Sunflower oil was selected due to its neutral sensory properties and widespread use in functional property studies, which ensures methodological consistency and comparability (Bessa *et al.*, 2022; Djordjević *et al.*, 2023; Lehmad *et al.*, 2025; Mshayisa and Van Wyk, 2021; Vanqa *et al.*, 2022).

Emulsion capacity and emulsion stability: The emulsion capacity (EC) and emulsion stability (ES) were evaluated according to the method described by Mshayisa and Van Wyk (2021), with slight modifications. The samples were first diluted in a 1% (w/v) solution of distilled water, and then 15 ml of this dispersion was homogenized with an equal volume of sunflower oil for 3 min at 1120 × *g* using a Polytron PT 3000 (Kinematica, Littau, Switzerland). Following this step, the samples underwent centrifugation (Hettich Universal 320 R, Tuttlingen, Germany) for 5 min at a force of 3220 × *g*, allowing for measurement of the volumes in each layer. To evaluate emulsion stability, the samples were heated at 80 °C for 30 min prior to centrifugation. Equations (12) and (13) were employed to calculate EC and ES, respectively.

$$\text{EC (\%)} = \frac{V_e}{V_T} \times 100 \tag{12}$$

$$\text{ES (\%)} = \frac{V_{30}}{V_e} \times 100 \tag{13}$$

In this context, V_e refers to the volume of the emulsified layer, V_T signifies the total volume of the contents within the tube, and V_{30} indicates the volume of the emulsified layer following 30 min of heating.

Foam capacity and foam stability: The procedure outlined by Zielinska *et al.* (2018) was utilized to assess foaming capacity (FC) and foam stability (FS), with minor adjustments. A 1% sample was prepared by homogenizing 20 ml of distilled water at 1120 × *g* for 4 min using a Polytron PT 3000 (Kinematica, Littau, Switzerland). The whipped mixture was then quickly transferred to a graduated cylinder for volume measurement, both immediately after homogenization and again after 30 min. FC and FS were calculated using equations (14) and (15).

$$\text{FC (\%)} = \frac{V_0 - V}{V} \times 100 \tag{14}$$

$$\text{FS (\%)} = \frac{V_{30}}{V_0} \times 100 \tag{15}$$

TABLE 1 Evaluation of drying time, yield, specific electrical energy consumption (SEEC), and average drying rate (ADR) of black soldier fly larvae using various drying methods

Drying method	Drying time (h)	Yield (%)	SEEC (kWh/kg)	ADR (kg water/kg (dm · h))
SD	120 ± 5.32[a]	39.06 ± 0.58[a]	0.00 ± 0.00[d]	0.01 ± 0.00[e]
HSED	6 ± 1.20[c]	38.5 ± 0.39[bc]	1.62 ± 0.02[c]	0.29 ± 0.01[c]
VFD	72 ± 3.05[b]	37.50 ± 0.55[d]	206.86 ± 8.71[a]	0.02 ± 0.00[d]
GD	5 ± 0.15[d]	38.28 ± 0.50[c]	0.00 ± 0.00[d]	0.34 ± 0.01[b]
MD	0.33 ± 0.01[e]	38.70 ± 0.24[b]	3.24 ± 0.1[b]	5.16 ± 0.63[a]

In this context, V_0 denotes the volume post-whipping, V represents the volume prior to whipping, and V_{30} indicates the volume recorded 30 min following the whipping process.

Structural and thermal analysis

Scanning electron microscopy (SEM) analysis: The surface microstructure of the dried larvae was examined using SEM. To reduce surface charging effects, the samples were coated with carbon utilizing a carbon coater (Cressington 108 carbon/A). Imaging was then conducted with a scanning electron microscope (VEGA3 TESCAN SEM, Topcon, Japan) at an acceleration voltage of 10 kV, capturing images at magnifications between 1000× and 2000×.

Thermal gravimetric analysis (TGA): The thermal degradation properties were assessed using a thermogravimetric analyser (TA Instruments Q500, New Castle, DE, USA). Approximately 25 mg of each sample was placed in the heating pan, and to mitigate thermo-oxidative effects, the analysis was conducted in a nitrogen atmosphere. The temperature was gradually increased from 25 °C to 600 °C at a constant heating rate of 10 °C/min utilizing the ramp mode.

Fourier transform infrared spectroscopy (FTIR): FTIR spectra were collected using a Bruker Vertex 70 DTGS Fourier transform infrared spectrometer with KBr pellets. The spectra were recorded by averaging 32 scans at a resolution of 2 cm^{-1}, covering a wavenumber range from 4000 to 400 cm^{-1}.

Statistical analysis

The experiments were conducted in triplicate, with results reported as mean values ± standard deviation. Statistical analysis was performed using one-way ANOVA, followed by Tukey's post hoc test for multiple comparisons. All analyses were carried out using IBM SPSS Statistics (Version 25.0, SPSS, Chicago, IL, USA), and significance was established at a P-value < 0.05. Data visualization was carried out using Origin 2021 software (OriginLab).

3 Results and discussion

Comparison of drying time, yields, specific electrical energy consumption (SEEC), and average drying rate (ADR)

Table 1 illustrates the significant differences among the drying methods concerning drying time, energy consumption, yield, and drying rate.

Despite being energy-free (SEEC = 0 kWh/kg), SD took the longest time (120 h) and had the lowest drying rate (ADR = 0.01 kg water/kg dm.h) due to its full dependence on natural conditions like ambient temperature, relative humidity, solar radiation, and wind speed. Interestingly, the SD method resulted in the highest yield (39.06%), which could be attributed to its lower drying efficiency. The prolonged drying period and the low drying temperature likely led to incomplete moisture removal, leaving the final moisture content of the sample the highest (7.87 ± 0.09%) among the studied methods. Thus, the higher moisture retention in the product contributed to the increased yield percentages, as noted in previous studies (Hu *et al.*, 2023). Although this inefficiency makes SD unsuitable for large-scale applications, it remains a cost-effective and sustainable option for small-scale uses.

In contrast, HSED, which also uses solar energy with added electrical support, significantly reduces drying time to just 6 h while achieving a yield of 38.5%, close to that of SD. Additionally, with a SEEC of only 1.62 kWh/kg, HSED offers an efficient balance between rapid processing and sustainable energy use. According to Lehmad *et al.* (2024b), this method is not only environmentally friendly and cost-effective but also emerges as a more feasible option for scaling up production, particularly where time and energy savings are crucial for operational efficiency.

On the other hand, VFD consumes a substantial amount of energy (SEEC = 206.86 kWh/kg) due to its reliance on very low temperatures and vacuum conditions. Furthermore, VFD's ADR is also low (0.02 kg water/kg (dm · h)), reflecting its slow sublimation pro-

TABLE 2 Comparison of drying techniques on the proximate composition of black soldier fly larvae (n = 3; mean ± SE

Parameter	Raw	SD	HSED	VFD	GD	MD
Moisture content (wet basis)	65.36^{a} ± 0.97	7.07^{b} ± 0.09	6.21^{bc} ± 0.08	3.61^{d} ± 0.03	5.91^{c} ± 0.07	7.87^{b} ± 0.09
Crude protein (g/100 g)	45.10^{a} ± 0.80	37.63^{c} ± 0.36	42.03^{b} ± 0.11	44.63^{a} ± 0.45	33.36^{d} ± 0.86	40.50^{b} ± 2.35
Crude fat (g/100 g)	n.d.	26.05^{c} ± 0.18	32.05^{b} ± 1.62	34.80^{a} ± 0.12	24.71^{d} ± 0.44	29.98^{b} ± 1.17
Ash (g/100 g)	6.18^{d} ± 0.11	7.00^{c} ± 0.02	9.46^{b} ± 0.01	8.72^{b} ± 0.02	12.48^{a} ± 1.12	8.47^{b} ± 0.38
Carbohydrates (g/100 g)	–	22.25^{a} ± 0.41	10.25^{bc} ± 1.18	8.41^{d} ± 0.47	23.54^{a} ± 1.48	13.18^{b} ± 2.88
Energy (kcal/100 g)	–	473.97^{c} ± 2.73	497.57^{b} ± 11.54	525.36^{a} ± 2.81	450.00^{d} ± 7.91	484.54^{bc} ± 20.83

Values are presented as percentages (% or g/100 g) based on dry matter content. Different letters within the same row denote statistically significant differences (ANOVA 1, $P < 0.05$). n.d., the Soxhlet method was not applicable to this sample, as it cannot be performed on wet samples.

cess. According to Saucier *et al.* (2021), the waxy cuticle of BSFL can act as a barrier to desiccation, which may further hinder moisture removal during freeze-drying. Notably, VFD displayed the lowest yield (37.50%), with a recorded moisture content of 5.85 ± 0.07%. This reduction in moisture content may be attributed to the direct sublimation of moisture within the material during the VFD process, leading to minimized moisture levels and subsequently decreased yields (Le *et al.*, 2022). As a result, VFD proves unsuitable for industrial use due to its high cost and energy-intensive requirements, making it an impractical choice for large-scale production.

In comparison, GD effectively balances efficiency with a relatively short drying time of just 5 h while consuming no energy, akin to SD. However, GD achieves a slightly higher ADR of 0.34 kg water/kg (dm · h), making it a viable option for medium-scale drying operations. It is important to note, though, that the drying process in GD occurs under uncontrolled conditions, heavily reliant on natural factors. This lack of control can affect the quality of the final product, emphasizing the need for careful monitoring of the drying environment to optimize outcomes.

Lastly, MD achieves rapid drying in just 20 min and boasts the highest ADR of 5.16 kg water/kg dm.h, alongside a moderate SEEC of 3.24 kWh/kg. This efficiency is largely due to the internal heating of materials during the microwave drying process, which significantly enhances heat transfer (An *et al.*, 2022). While this method is optimal for scenarios where time is of the essence, its energy demands warrant careful consideration, especially at an industrial scale where the quantity of material to be processed is substantial.

Impact of drying on proximate composition

Drying is a widely used method to lower moisture content, effectively slowing microbial growth and minimizing chemical degradation. The impact of drying techniques on the proximate composition of BSFL is illustrated in Table 2.

In this study, the moisture content of dried BSFL fell below the safe threshold of 10%, as noted by Djordjević *et al.* (2023), ranging from 3.61% to 7.87%. This reduction ensures prolonged safe storage of the dried products. The VFD process achieved the lowest moisture content (3.61%, as shown in Table 2), due to its ability to remove water through sublimation under reduced pressure. This process is particularly efficient at extracting bound water, which is more difficult to remove via other drying methods. Similar observations have been reported in other studies (Demircan *et al.*, 2024). GD and HSED also significantly reduced moisture content (5.91% and 6.21%, respectively). The lower moisture levels in GD and HSED can be attributed to the high drying temperatures which accelerate water evaporation. In contrast, SD and MD resulted in slightly higher moisture content (7.87% and 7.07%, respectively). This can be due to the uncontrolled drying conditions and the shorter drying duration, respectively. These findings align with the studies by Lier *et al.* (2024) and Nyangena *et al.* (2020), which also reported higher moisture retention for these drying methods.

After drying, the protein content ranged from 33.36% to 44.63%, which is consistent with previously reported values for dried BSFL (Huang *et al.*, 2019; Saucier *et al.*, 2021). VFD retained the highest protein level (44.63 g/100 g) due to its low temperature of −60 °C, which minimizes denaturation. This finding aligns with studies by Monisha and Loganathan (2021) and Bubler *et al.* (2016), who investigated the effects of lyophilization on BSFL. HSED, MD, and SD resulted in moderate protein loss, with contents of 42.03 g/100 g, 40.50 g/100 g, and 37.63 g/100 g, respectively. This reduction can be attributed to the relatively high temperatures utilized in HSED, the intense yet brief heating in MD, and to the prolonged drying duration in SD. Similar trends were observed for drying edible stinkbug (Dandadzi *et al.*, 2023). In contrast, GD demonstrated the most significant decrease in protein content, with a reduction of 26.03% compared to raw larvae. This substantial loss can be attributed to uncontrolled drying conditions, the elevated drying temperature, and temperature fluctuations within the greenhouse that are not consistently optimal for protein preservation. The greenhouse effect may further exacerbate protein denaturation and degradation, leading to a decrease in the protein content of the larvae (Broudi *et al.*, 2022). Despite the impact of drying on protein content, the protein levels in dried BSFL still exceed those found in conventional sources such as beef, eggs, soybeans, and milk, where protein typically constitutes about 30% to 45% of dry matter (Churchward-Venne *et al.*, 2017). Furthermore, all dried larvae, except for those processed through GD, surpass the minimum protein content requirements (34%) set by leading companies in the insect market (EnviroFlight, 2023; Langley, 2018).

The crude fat content (24.71-34.80%) observed in this study falls within the range previously reported for BSFL in the literature (Saucier *et al.*, 2021; Zulkifli *et al.*, 2022). Among the drying methods, VFD preserved the highest fat content (34.80 g/100 g), followed by HSED (32.05 g/100 g) and MD (29.98 g/100 g), while GD yielded the lowest fat level (24.71 g/100 g). These variations suggest that drying methods that utilize lower temperatures, moderate and controlled environment, or faster processing – such as VFD, HSED, and MD, respectively, – tend to retain more fat. In contrast, methods involving higher, uncontrolled, and fluctuating temperatures, like GD, or prolonged drying periods with high oxygen exposure, as in SD, may accelerate lipid oxidation and degradation, leading to reduced fat retention (Zioud *et al.*, 2023). Similar behaviour was reported for drying bee larvae (Cao *et al.*, 2024).

The ash content (7.00-12.48%) observed in this study falls within the reported range for BSFL in the literature (3.8-14.61%) (Nyakeri *et al.*, 2017; Nyangena *et al.*, 2020). A significant increase ($P < 0.05$) in ash content was noted after drying, likely due to the concentration of minerals as moisture is reduced. Similar findings were reported by Dandadzi *et al.* (2023). The relatively high ash levels suggest that these samples are a valuable source of minerals.

Insects naturally contain high amounts of carbohydrates, primarily in the form of chitin, fibers, and complex carbohydrates like cellulose and lignin, which may also originate from the insect's gut content (Fombong *et al.*, 2017). Dried BSFL exhibited a high carbohydrate content ranging from 8.41% to 23.54%, aligning with the ranges previously reported for *Hermetia illucens* larvae (7.43-29.3%) (Nyangena *et al.*, 2020; Ravi *et al.*, 2020). GD resulted in the highest carbohydrate content (23.54 g/100 g), while VFD had the lowest (8.41 g/100 g). This significant variation is likely due to how different drying techniques impact the degradation of complex carbohydrates. In GD, the uncontrolled and high-temperature conditions may promote the breakdown of complex carbohydrates, releasing more free carbohydrates (Broudi *et al.*, 2022).

Energy content is directly influenced by the levels of macronutrients, particularly fats, proteins, and carbohydrates. The energy range observed in this study is consistent with findings by Vanqa *et al.* (2022) on BSFL, reinforcing its status as a valuable energy source. VFD exhibited the highest energy value (525.36 kcal/100 g), which correlates with its higher retention of crude fat and protein. In contrast, GD yielded the lowest energy content (450.00 kcal/100 g), despite having the highest carbohydrate levels. This reduced energy value is attributed to significant losses in protein and fat during GD, likely due to the elevated, fluctuating temperatures and uncontrolled drying conditions. Direct exposure to solar radiation during GD may further degrade these macronutrients, reducing the caloric density of the final product.

Impact of drying methods on physicochemical properties

Table 3 shows the effect of different drying methods on the physicochemical properties of BSFL.

Understanding the pH levels of dried BSFL is essential, as it influences their suitability for incorporation into various food matrices without affecting their functional properties. In this study, the pH of dried BSFL ranged from 7.90 to 8.84, indicating a slightly alka-

TABLE 3 Physicochemical properties of black soldier fly larvae subjected to various drying methods

Parameter	Raw	SD	HSED	VFD	GD	MD
pH	$8.80^{a} \pm 0.01$	$8.32^{c} \pm 0.02$	$8.55^{b} \pm 0.01$	$8.71^{ab} \pm 0.01$	$7.90^{d} \pm 0.01$	$8.84^{a} \pm 0.02$
L^*	$46.56^{b} \pm 1.90$	$39.38^{cd} \pm 1.11$	$42.01^{c} \pm 0.43$	$63.57^{a} \pm 0.77$	$25.03^{e} \pm 3.20$	$38.88^{d} \pm 1.05$
a^*	$3.04^{d} \pm 0.67$	$6.62^{b} \pm 0.09$	$5.55^{c} \pm 0.39$	$1.67^{e} \pm 0.08$	$14.37^{a} \pm 1.31$	$6.51^{b} \pm 0.63$
b^*	$14.37^{d} \pm 0.17$	$19.41^{b} \pm 0.40$	$18.88^{b} \pm 0.32$	$15.27^{d} \pm 0.52$	$17.70^{c} \pm 0.50$	$23.53^{a} \pm 0.21$
ΔE	–	$9.80^{c} \pm 1.06$	$7.18^{c} \pm 1.23$	$20.08^{b} \pm 1.60$	$24.71^{a} \pm 2.21$	$4.90^{d} \pm 1.69$
c^*	$14.70^{c} \pm 1.11$	$20.51^{ab} \pm 0.35$	$19.68^{b} \pm 0.31$	$15.38^{c} \pm 0.62$	$22.84^{a} \pm 0.47$	$24.43^{a} \pm 0.03$
h^*	$78.11^{b} \pm 2.33$	$71.17^{c} \pm 0.59$	$73.61^{b} \pm 1.17$	$83.85^{a} \pm 2.69$	$50.99^{d} \pm 3.30$	$74.53^{b} \pm 1.52$
BI	–	$16.84^{c} \pm 0.42$	$13.90^{d} \pm 0.78$	$4.26^{e} \pm 0.97$	$45.80^{a} \pm 5.10$	$18.02^{bc} \pm 1.51$
BD (g/ml)	n.d.	$0.65^{b} \pm 0.02$	$0.69^{ab} \pm 0.02$	$0.53^{d} \pm 0.01$	$0.91^{a} \pm 0.50$	$0.60^{c} \pm 0.02$
Ca (mg/100 g)	$3100^{e} \pm 9.00$	$3200^{d} \pm 30.71$	$3248^{b} \pm 5.35$	$3260^{a} \pm 10.20$	$3228^{c} \pm 16.00$	$3240^{b} \pm 15.50$
K (mg/100 g)	$1280^{e} \pm 10.15$	$1350^{a} \pm 8.81$	$1342^{b} \pm 5.20$	$1336^{bc} \pm 3.04$	$1318^{d} \pm 8.00$	$1325^{c} \pm 4.65$
Mg (mg/100 g)	$211^{e} \pm 0.13$	$271^{b} \pm 1.83$	$272^{b} \pm 2.11$	$259^{c} \pm 3.70$	$285^{a} \pm 1.01$	$236^{d} \pm 5.23$
Na (mg/100 g)	$124^{d} \pm 12.30$	$177^{a} \pm 5.10$	$174^{a} \pm 10.55$	$150^{b} \pm 5.00$	$133^{c} \pm 2.00$	$140^{bc} \pm 8.71$
Fe (mg/100 g)	$23.00^{d} \pm 0.60$	$41.35^{b} \pm 2.33$	$41.00^{b} \pm 1.50$	$40.61^{b} \pm 3.07$	$48.12^{a} \pm 2.70$	$34.60^{c} \pm 5.60$
Zn (mg/100 g)	$18.88^{c} \pm 2.06$	$28.02^{b} \pm 0.85$	$23.60^{b} \pm 2.50$	$29.65^{a} \pm 0.14$	$30.77^{a} \pm 1.19$	$28.46^{b} \pm 0.45$
Mn (mg/100 g)	$6.08^{c} \pm 0.03$	$13.33^{a} \pm 1.00$	$13.21^{ab} \pm 1.50$	$13.20^{b} \pm 0.05$	$14.20^{a} \pm 0.75$	$12.72^{b} \pm 0.12$
Cu (mg/100 g)	$0.70^{d} \pm 0.02$	$3.33^{b} \pm 0.08$	$3.21^{b} \pm 0.01$	$3.20^{b} \pm 0.03$	$4.21^{a} \pm 0.50$	$2.72^{c} \pm 0.01$

Different letters in the same row represent statistically significant differences (ANOVA 1, $P < 0.05$). n.d., Bulk density measurements can not be performed on wet samples.

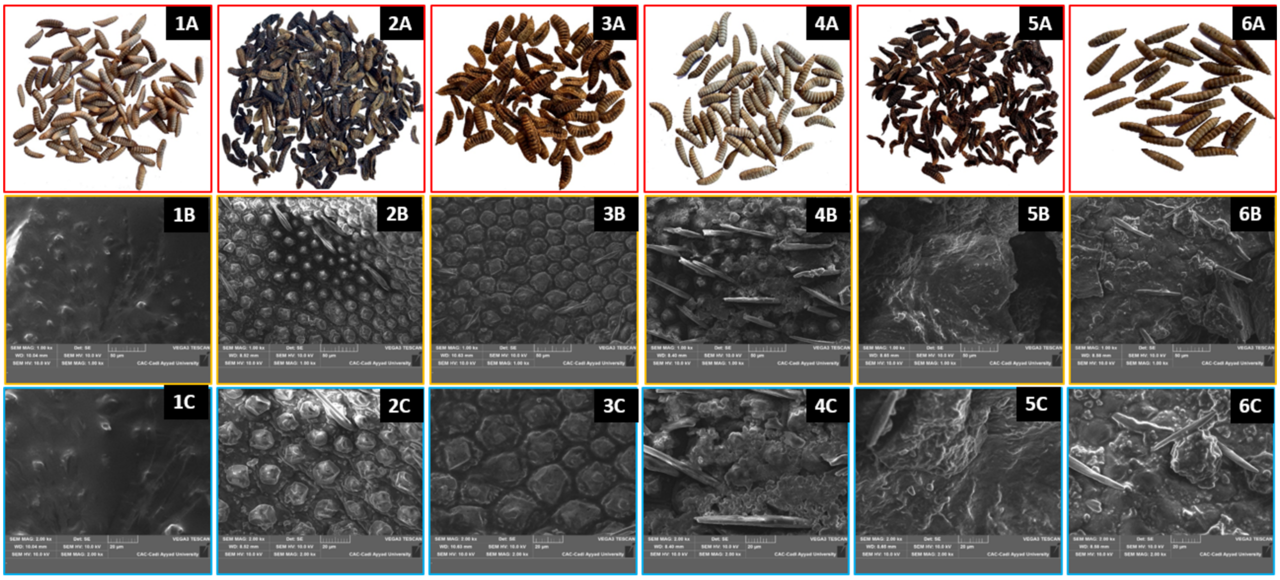

FIGURE 2 Scanning electron microscopy images of raw (1), SD (2), HSED (3), VFD (4), GD (5), and MD (6) larvae, and their corresponding real images (A). Scale bars: 50 µm (B) and 20 µm (C).

line nature. These findings align with previous research on blanched BSFL (Larouche *et al.*, 2019). The drying method employed significantly affected the pH levels, with the lowest values observed in GD samples. This reduction in pH may be attributed to the thermal breakdown of lipids during the drying process, leading to the release of free fatty acids and increased fat acidity (Zhen *et al.*, 2020).

Regarding colour parameters, lightness (L^*) is significantly affected by the drying method, with VFD producing the lightest sample (63.57) (Figure 2-4A), while GD results in the darkest sample (25.03) (Figure 2-5A). This significant difference indicates a pronounced browning effect in GD, as evidenced by its highest browning index (BI) value of 45.80, likely attributed to uncontrolled high temperatures and the greenhouse effect.

Similarly, redness (a^*) peaks in GD at 14.37, suggesting enhanced Maillard reactions and pigment alterations, while VFD registers the lowest value at 1.67. The yellowness (b^*) also follows this trend, with MD exhibiting the highest b^* value, indicating that MD samples are more yellow (Figure 2-6A). Additionally, the colour difference (ΔE) is greatest in GD at 24.71, signalling significant visual changes compared to the raw larvae. The chroma (c^*) values indicate that GD produces the most intense colour, while VFD retains the lower c^*. Notably, HSED exhibits moderate colour values (Figure 2-3A), with the lowest ΔE, indicating that this method effectively preserves colour attributes compared to raw larvae. This preservation may be attributed to reduced pigment loss facilitated by the controlled drying conditions and shorter drying time. Similar findings regarding the impact of drying methods on colour parameters have been reported for tomato waste (Çetin, 2022), aronia fruit (Demircan *et al.*, 2024) and kiwifruit pomace (Zhang *et al.*, 2024).

Bulk density (BD), which measures the mass of powder per unit volume in its natural, untapped state, offers valuable insights into the packing efficiency and compactness of powders. In this study, the BD of BSFL powders ranged from 0.53 to 0.91 g/ml, aligning with previous studies on BSFL, which documented values between 0.51 and 1.01 g/ml (Mshayisa *et al.*, 2022; Vanqa *et al.*, 2022). The lowest BD was observed in the VFD samples, likely due to the method's preservation of structural integrity, resulting in a more porous, less compact structure. Conversely, the highest BD values were recorded for GD and HSED samples, indicating that these methods produce denser, more compact powders. The application of high temperatures in GD and HSED likely caused greater structural collapse, reducing porosity and increasing density. These higher densities offer practical benefits, such as improved compactness and packing efficiency, leading to cost savings in storage and transportation (Koç *et al.*, 2021). A similar trend in BD was noted in dried curry leaves processed with various drying techniques (Negi *et al.*, 2025).

The mineral content of BSFL in this study aligns with findings from previous research by Bessa (2016) and Zulkifli *et al.* (2022) on the same insect species, though slightly lower than the values reported by Smets *et al.* (2020). This variation could be attributed to differences in rearing conditions, feed composition, or drying methods employed. Nevertheless, the mineral levels in BSFL were significantly higher compared to other edible insects, such as *Tenebrio molitor* (mealworms) (Selaledi and Mabelebele, 2021), *Ruspolia differens* (edible grasshoppers) (Fombong *et al.*, 2017), and *Encosternum delegorguei* (stink bugs) (Dandadzi *et al.*, 2023). Ca, K, and Mg are the predominant minerals in the composition of dried BSFL, with average concentrations of 3235 mg/100 g, 1334 mg/100 g, and 264 mg/100 g, respectively. The drying methods had a notable effect on the mineral profile of BSFL, with dried larvae showing higher mineral levels compared to raw larvae, primarily due to the concentration effect caused by moisture removal (Kumar *et al.*, 2023). VFD yielded the highest Ca content at 3260 mg/100 g, while SD resulted in the lowest Ca concentration at 3200 mg/100 g. The highest K content was observed in samples dried using SD, while the lowest was found in those processed with GD. The GD samples exhibited the highest concentrations of Mg, Fe, Zn, Mn, and Cu, which was expected given their low moisture content and high ash content. These factors typically lead to higher mineral concentrations due to moisture reduction. In contrast, the MD method resulted in the smallest increases in Mg, Fe, Mn, and Cu compared to the other drying methods, despite similar moisture loss, suggesting that the shorter drying time or rapid heating may have affected mineral retention (Arslan *et al.*, 2010). Overall, dried BSFL, regardless of the drying method used, results in a product with an impressive mineral profile, surpassing the recommended daily intake (RDI) for most essential minerals in adult humans. The only exception is potassium, which falls short of the adult RDI of 4700 mg (FAO/WHO/UNU, 1985). Given the high levels of key minerals such as Ca, Fe, Mg, and Zn, incorporating BSFL into diets, particularly in developing countries, could be a valuable strategy to combat micronutrient deficiencies.

Techno-functional properties

The impact of different drying methods on the techno-functional properties of BSFL is depicted in Table 4.

BSFL powder has potential for use as a food additive, where its functional properties, such as WBC and OBC, are crucial. The WBC and OBC values obtained in this study were comparable to those reported in the literature for *Hermetia illucens* flour (Bessa *et al.*, 2022), though lower than those of *Imbrasia oyemensis* flour (Akpossan *et al.*, 2015). Drying methods had a significant impact on both WBC and OBC. VFD resulted in the highest WBC and OBC, followed by HSED and MD. In contrast, SD and GD showed the lowest values. A similar trend was observed for drying kiwifruit pomace (Zhang *et al.*, 2024), where vacuum freeze drying, vacuum drying, and vacuum microwave drying better pre-

TABLE 4 Techno-functional properties of dried larvae using various drying methods (n = 3; mean ± SE)

Parameter	Raw	SD	HSED	VFD	GD	MD
WBC (%)	71.11^{f} ± 0.28	74.50^{d} ± 0.66	80.05^{b} ± 2.00	89.43^{a} ± 0.43	71.44^{e} ± 1.10	78.81^{c} ± 3.55
OBC (%)	60.55^{e} ± 2.70	74.13^{cd} ± 1.33	85.58^{b} ± 0.32	92.77^{a} ± 1.37	69.25^{d} ± 2.18	86.18^{b} ± 0.20
EC (%)	35.22^{c} ± 0.11	33.51^{d} ± 2.70	39.12^{ab} ± 1.84	42.55^{a} ± 0.32	20.87^{e} ± 0.30	39.85^{ab} ± 1.41
ES (%)	28.20^{d} ± 0.15	22.06^{e} ± 1.58	35.06^{b} ± 0.62	41.72^{a} ± 1.10	5.45^{f} ± 0.33	32.06^{c} ± 0.58
FC (%)	17.10^{ab} ± 2.13	6.03^{c} ± 0.15	12.54^{b} ± 0.22	18.06^{a} ± 0.27	1.59^{d} ± 4.86	13.74^{b} ± 0.12
FS (%)	49.55^{c} ± 5.80	47.16^{d} ± 2.06	55.11^{b} ± 1.70	81.34^{a} ± 0.33	34.40^{e} ± 3.00	52.40^{bc} ± 1.66

Distinct letters in the same row indicate significant differences (ANOVA 1, $P < 0.05$).

served hydration properties due to their ability to maintain structural integrity, while thermal methods like sun drying and hot air drying led to lower WBC and OBC values. The differences in WBC and OBC are due to how drying methods affect the structural integrity of BSFL (Llavata *et al.*, 2022). Methods like VFD preserve the porous structure, enhancing water and oil retention, while higher heat methods like GD cause structural collapse, reducing binding capacity, as shown in Figure 2. Moreover, protein content plays a crucial role in these capacities. As observed by Aguilera *et al.* (2021), larvae with higher protein levels exhibited greater WBC and OBC due to the ability of proteins to retain water and oil within their three-dimensional structure. However, Lee *et al.* (2019) highlighted that higher temperatures and drying time lead to protein denaturation and aggregation, causing the protein network to collapse, which significantly diminishes the ability to retain water and oil.

EC refers to a molecule's ability to facilitate the solubilization or dispersion of two immiscible liquids, while ES is the ability to maintain the integrity of the emulsion over time (Lucas *et al.*, 2019). In general, EC values above 40% and ES values above 30-50% are considered desirable for effective emulsification and stability in food systems (Norn, 2015). According to Table 4, the EC of BSFL powders is relatively favourable compared to some traditional emulsifiers such as egg yolk (13.38%) and soy flour (18%) but remains lower than that of lentil flour (65.75%) and chickpea flour (61.14%) (Kudre *et al.*, 2018; Zielinska *et al.*, 2018). However, the ES of BSFL powders is considerably lower than that of conventional emulsifiers known for their high stability, including egg yolk (100.81%), lentil flour (91.99%), and chickpea flour (94.19%) (Kudre *et al.*, 2018; Zielinska *et al.*, 2018). Concerning the impact of drying methods, a similar trend to that observed for WBC and OBC was noted for EC and ES. VFD and HSED demonstrated superior emulsifying capacity and stability, while GD exhibited the lowest values. This can be attributed to the reduction in protein content and denaturation caused by heat, which diminishes protein functionality (Bessa *et al.*, 2022). High temperatures and uncontrolled conditions during GD lead to structural changes in proteins, impairing their ability to effectively stabilize emulsions. The EC and ES values obtained for BSFL via VFD (42.45% and 41.72%, respectively) were higher than those reported by Ndiritu *et al.* (2017) for freeze-dried house cricket powder (26.83% for EC and 21.86% for ES). However, the values for VFD BSFL were lower than those reported for freeze-dried house cricket (58.87% for EC and 95% for ES). These differences are likely due to variations in insect species, composition, rearing conditions, and processing methods.

FC and FS are key functional properties that indicate the ability of a material to form and maintain stable foams, which is important for food processing and product texture. The FC (1.59-18.06%) and FS (34.40-81.34%) observed in this study fall within the range for FC and are higher for FS compared to values reported for yellow mealworm (16.67% for FC and 23% for FS) (Aguilera *et al.*, 2021). In contrast, traditional foaming agents like egg white show significantly higher FC (145.50%) and FS (151.10%) values compared to those found in this study (Kudre *et al.*, 2018). Drying methods had a significant effect on foaming properties, with VFD exhibiting the highest foaming capacity due to minimal protein denaturation (Bals and Kulozik, 2003). Previous studies have shown that the high carbohydrate content in mealworms promotes passive protein-protein interactions, leading to lower foaming capacity because of the formation of a fragile interfacial membrane during foam generation (Lee *et al.*, 2019). Our study supports this, as samples with higher carbohydrate content, such as GD (23.54%) and SD (22.25%), displayed lower foaming properties. Conversely, samples with lower carbohydrate content, like VFD (8.41%) and HSED (10.25%), exhibited better foaming properties.

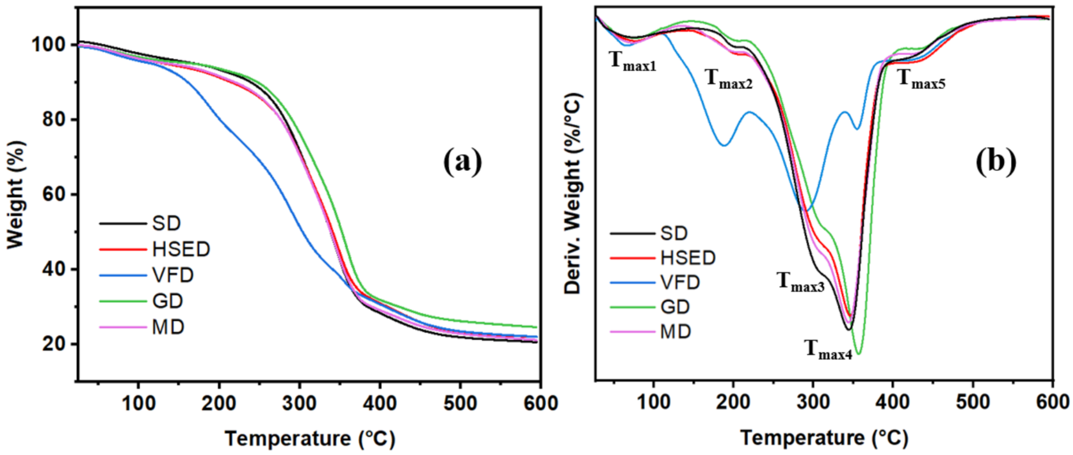

FIGURE 3 TGA/DTG curves of dried black soldier fly larvae using various drying method, (a) TGA and (b) DTG.

Structural and thermal analysis

Scanning electron microscopy (SEM) analysis: Figure 2 illustrates the SEM analysis, which allow for an evaluation of the effects of different drying methods on the surface structure of BSFL.

In the raw larvae (Figure 2-1), the surface is smooth, with intact and well-structured cuticle layers. No visible damage is observed, reflecting the natural, undisturbed state of the larvae before any processing. In contrast, SD (Figure 2-2), conducted over five days under fluctuating temperatures, results in noticeable surface shrinkage and deformation. At the 50 μm scale (Figure 2-2B), small cracks and an uneven texture are evident, while at 20 μm (Figure 2-2C), the hexagonal exoskeleton pattern is distorted, with some areas collapsing. The slow, uneven drying process, likely due to temperature variations, causes moderate structural damage. On the other hand, the HSED (Figure 2-3), performed at a controlled 60 °C for 6 h, results in a more uniform surface with fewer cracks compared to solar drying. At 50 μm (Figure 2-3B), the surface appears smoother, and at 20 μm (Figure 2-3C), the hexagonal structure remains mostly intact, with only slight deformation. The controlled temperature helps preserve the structure better than solar drying, offering a good balance between efficiency and structural preservation. VFD (Figure 2-4) provides the best preservation of the surface structure, with a porous texture visible at both magnifications. The hexagonal pattern is almost identical to that of the raw larvae, indicating minimal disruption. This gentle moisture removal method maintains the structural integrity very effectively. Similar findings were found for freeze dried *Ganoderma lucidum* (Ashikhmina *et al.*, 2024). In contrast, GD (Figure 2-5) causes the most significant surface alteration. The SEM images show severe cracking, roughness, and a heavily distorted hexagonal structure. The high drying temperatures and direct exposure to solar radiation within the chamber, amplified by the greenhouse effect, lead to extensive surface damage, making this the most deteriorated sample. A similar pattern was observed in greenhouse-dried pomegranate arils (Broudi *et al.*, 2022). Lastly, MD (Figure 2-6) also results in considerable surface damage. Large cracks and fragmented structures are visible, with the rapid and intense drying process severely compromises the surface's integrity.

Thermal gravimetric analysis: The thermogravimetric analysis (TGA) curve in Figure 3 (a) represents the weight loss of BSFL subjected to various drying methods as a function of increasing temperature from 25 to 600 °C. The curve shows three distinct stages of weight loss.

The first stage (50-150 °C) primarily reflects the loss of moisture and volatile compounds (Keerthi Reddy *et al.*, 2024). This stage is consistent across all drying methods, though VFD shows a slower initial weight loss due to its effective sublimation process, leaving only 3.61% residual moisture. This indicates a lower amount of bound water in the sample, which is typical for freeze-dried materials where moisture is effectively removed (Demircan *et al.*, 2024).

The second stage of decomposition (150-380 °C) involves the thermal degradation of organic components such as proteins, lipids, and carbohydrates, including chitin (Elkadaoui *et al.*, 2024b; Lawal *et al.*, 2022; Zozo *et al.*, 2022). In VFD samples, degradation begins earlier due to the presence of heat-sensitive volatile compounds that are preserved after freeze-drying but have already degraded in conventional heat-drying methods. Although the degradation in VFD samples is slower compared to other methods – where it tends to be more rapid and sharp – the overall weight loss is more substantial. This can be attributed to several factors. First, the porous structure of freeze-dried materials (as shown by SEM analysis; Figure 2-4) accelerates thermal degradation. As the structure collapses under heat, faster weight loss occurs compared to the denser, more compact structures in samples from other drying methods (Hu *et al.*, 2023). Additionally, VFD minimizes protein denaturation, preserving proteins in their native, thermally sensitive state. This higher protein content (44.63 g/100 g) contributes to more significant weight loss in this region (Brishti *et al.*, 2020; Ghribi *et al.*, 2015). Furthermore, lipid degradation, which becomes significant after 250 °C, is delayed in the VFD sample due to its higher fat content (34.80 g/100 g), contributing to the slower overall degradation compared to other drying methods.

The final decomposition stage (380-550 °C) reflects the breakdown of more thermally stable organic matter, including polypeptides and saturated fatty acids (Huang *et al.*, 2019; Lawal *et al.*, 2022; Mshayisa *et al.*, 2022). By this point, the differences between drying methods diminish, as what remains is primarily inorganic residues (e.g. minerals) that are more resistant to further degradation, with char residue ranging from 20.55 to 24.56%, as detailed in Table S1 (Masite *et al.*, 2022).

Figure 3b illustrates the derivative weight loss (DTG) as a function of temperature for BSFL dried using different methods, highlighting the temperatures at which maximum thermal decomposition occurs. These peaks are associated with the degradation of specific biochemical components, helping to pinpoint the most significant stages of thermal breakdown for each drying method, as detailed in Table S1. All samples exhibit a similar thermal decomposition pattern, showing five degradation peaks, but with varying peak amplitudes across the different drying methods. The first degradation peak (T_{max1}, between 63 and 75 °C) is associated with the loss of bound water, representing residual moisture or weakly bonded water molecules within the sample (Soetemans *et al.*, 2020). The second peak (T_{max2}, between 188 and 200 °C), likely corresponds to the thermal degradation of organic compounds, such as proteins and heat-sensitive amino acids (Masite *et al.*, 2022; Weiss *et al.*, 2018). This peak is sharper and more prominent in VFD samples due to their higher protein content, suggesting that VFD better preserves sensitive components like proteins. The third peak (T_{max3}, between 290 and 314 °C) marks the degradation of lipids, including triglycerides and unsaturated fatty acids. The most significant mass loss occurs between 344 and 356 °C (T_{max4}), likely due to the breakdown of more complex organic materials, such as chitin, residual proteins that degrade at higher temperatures, and further decomposition of unsaturated fatty acids, including peroxidation of polyunsaturated fatty acids (Elkadaoui *et al.*, 2024b; Lawal *et al.*, 2022; Masite *et al.*, 2022; Soetemans *et al.*, 2020). The final peak (T_{max5}, between 429 and 441 °C) corresponds to the breakdown of more thermally stable components, such as saturated fatty acids, as well as recalcitrant carbon structures like char and any remaining organic matter that requires higher temperatures for complete decomposition (Al-Harrasi *et al.*, 2022).

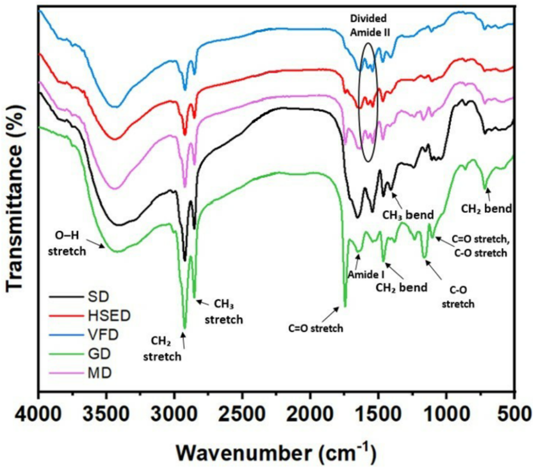

FIGURE 4 Effect of drying methods on the functional groups of black soldier fly larvae via FTIR spectra.

Considering the thermal stability of the samples, HSED and MD provide superior thermal stability, as indicated by the broader DTG peaks, which suggest a slower degradation of organic components like proteins and fats. In comparison, SD and GD show similar thermal profiles, but GD displays a slightly sharper peak at T_{max4}, suggesting faster decomposition in GD than in SD. VFD, although effective in preserving sensitive materials such as proteins during freeze-drying, exhibits rapid degradation upon heating.

Functional groups analysis: The FTIR spectra analysis illustrated in Figure 4 was conducted to evaluate the changes in the chemical structure of dried BSFL by means of diverse methods. Various spectral regions corresponding to different functional groups can be distinguished across the spectra of the dried samples, as detailed in Table S2.

In the region of 3437-3417 cm^{-1}, a broad peak is observed, attributed to the stretching vibrations of the O-H bond, typically associated with water molecules, phenolic compounds, amino acids, and chitin (Bogusz *et al.*, 2024; Elkadaoui *et al.*, 2024a; Orkusz *et al.*, 2024). The GD samples exhibit significantly higher transmittance, indicating a greater degree of bio-molecular denaturation, likely due to the heating process causing more structural changes.

The stretching vibrations of the C-H bonds in the -CH_2 and -CH_3 alkyl groups are observed around 2925 cm^{-1} and 2855 cm^{-1}, indicating the presence of fatty acids and chitin (Orkusz *et al.*, 2024; Zozo *et al.*, 2022). Additionally, the strong band at 2925 cm^{-1} may also correspond to the C-H stretching vibrations of the amide B group, which is associated with protein structures (Bogusz *et al.*, 2024; Queiroz *et al.*, 2021).

A distinct IR band around 1742 cm^{-1}, absent in the SD spectra, is likely associated with the C = O stretching vibrations of ester groups in lipids (Zozo *et al.*, 2022). The strong transmittance in GD, followed by MD, suggests that the thermal processing may cause the degradation or transformation of lipid ester groups, resulting in the breakdown of ester bonds. The absence of this band in SD samples could be attributed to the extended drying period (5 days with fluctuating temperatures), which may have caused complete degradation of lipid esters.

In the amide region associated with proteins and chitin in BSFL meal (Azzi *et al.*, 2024; Bogusz *et al.*, 2022; Queiroz *et al.*, 2021), the amide I band, linked to the stretching vibrations of the carbonyl group (C = O), appears at approximately 1645 cm^{-1} across all samples. The amide II region exhibits two distinct bands at around 1544 cm^{-1} and 1575 cm^{-1} (referred to as divided amide II), corresponding to in-plane N-H bending and C-N stretching vibrations (Elkadaoui *et al.*, 2024a; Queiroz *et al.*, 2021). Protein quality and structural integrity, primarily influenced by the amide I and II bands due to the sensitive nature of the C = O bond (Mshayisa *et al.*, 2022), were better preserved in the VFD and HSED samples, followed by the MD sample, as indicated by lower transmittance. In contrast, SD and GD methods exhibited higher transmittance, suggesting more significant protein denaturation.

The bands in the 1460-1300 cm^{-1} range are attributed to the bending vibrations of -CH_2 and -CH_3 groups commonly found in lipids, such as fatty acids (dos Santos *et al.*, 2021; Orkusz *et al.*, 2024). Meanwhile, the bands within the 1200-1000 cm^{-1} region correspond to C-O stretching and -C = O stretching, typically associated with carbohydrates (Queiroz *et al.*, 2021).

The Amide III band was identified at 1242 cm^{-1}, as noted by Zhang *et al.* (2022). This region corresponds to the combination of C-N stretching vibrations and N-H deformation associated with amide linkages.

The band at around 1170 cm^{-1} is primarily associated with C-O stretching in esters, which are commonly found in lipids such as triglycerides and phospholipids, as well as in carbohydrates (Orkusz *et al.*, 2024). The variation in intensity across different drying methods suggests differences in the preservation of esterified lipids. In the case of VFD, a weaker peak may indicate improved preservation of lipids.

The final band observed at approximately 720 cm^{-1}, which is very intense in GD samples, can be attributed to a weak rocking vibration of -(CH_2)-(CH_3) groups. These groups are typically associated with long-chain aliphatic hydrocarbons and likely indicate the presence of fatty acids (Lerma-García *et al.*, 2010).

FTIR analysis indicated that the transmittance levels varied among the drying methods, with the lowest transmittance – and thus the greatest concentration of functional groups – observed in larvae dried using VFD and HSED. In contrast, GD resulted in the lowest concentration due to greater molecular degradation from high temperatures. Overall, while the IR patterns were consistent, variations in transmittance intensity reflected differences in the concentrations of lipids, chitin, and proteins, aligning with findings reported in the literature (Al-Harrasi *et al.*, 2022; Kumar *et al.*, 2023).

4 Conclusion

This study investigated the effects of five drying methods – sun drying (SD), hybrid solar-electric drying (HSED), vacuum freeze drying (VFD), greenhouse drying (GD), and microwave drying (MD) – on black soldier fly larvae (BSFL). We assessed each method's impact on yield, specific electrical energy consumption, average drying rate, and the nutritional, physicochemical, techno-functional, structural, and thermal properties of BSFL. Among the methods, VFD proved to be the most effective in preserving nutrients, physicochemical properties, techno-functional qualities, and the microstructure of BSFL. However, the method's scalability is limited by its lower yield (37.5%), high energy consumption (206.86 kWh/kg), and long drying time (72 h). In contrast, HSED presented several advantages, such as a significantly shorter drying time (6 h) and much lower energy consumption (1.62 kWh/kg), while achieving drying quality comparable to that of VFD. These attributes make HSED a promising technique for BSFL processing, as it preserves product quality and enhances drying efficiency. Its sustainable and eco-friendly characteristics position HSED as a viable option for large-scale applications with a reduced environmental impact. In contrast, GD was the least effective method, resulting in the greatest nutrient loss, especially in proteins and lipids, along with severe structural and colour degradation. High temperatures and direct solar exposure, amplified by the greenhouse effect, caused extensive surface damage, indicating that GD significantly compromised the quality of the larvae. Overall, this research provides valuable insights for optimizing drying processes to enhance the quality of BSFL. These findings can inform future efforts to refine processing techniques, ensuring the production of high-quality larvae suitable for a wide range of applications in the food and feed industries.

Supplementary materials

Data is available on https://doi.org/10.1163/23524588-bja10272 under Supplementary Materials.

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Author contributions

Manal Lehmad: Writing (original draft, review and editing), methodology, investigation, resources, formal analysis, data curation, conceptualization; Brahim Nomeir: formal analysis, data curation, resources, writing (review and editing); Nawfal Hidra: formal analysis, data curation. patrick lhomme: resources, data curation, writing (review and editing); Youssef El Hachimi: validation, supervision, project administration. Naji Abdenouri: validation, supervision, project administration, writing (review and editing).

Conflict of 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.

Data availability

Data will be made available on request.

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