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EFFECT OF HEATING PRETREATMENT AND DRYING TEMPERATURE ON THE CHARACTERISTICS OF DRIED BLACK SOLDIER FLY (*HERMETIA ILLUCENS*) LARVAE

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Black soldier fly larvae (BSFL) offer significant environmental and nutritional benefits, including organic waste reduction and utility as a supplemental feed ingredient. This study investigated the effects of heating pretreatment and drying temperature on the physicochemical characteristics of dried BSFL. A factorial experimental design was employed, combining two pretreatment methods (immersion in hot water [90–95 °C] and steaming) with three drying temperatures (42 °C, 50 °C, 58 °C), yielding six treatment groups with triplicate samples. Analysed parameters included yield, colour, moisture content, ash content, protein content, and lipid content. Drying at 58 °C with hot water immersion pretreatment yielded optimal results: the highest protein content (42.203% ±0.381%), lowest moisture content (2.427% ±0.131%), and favourable lipid (27.18% ±2.71%) and ash (14.833% ±1.81%) levels, alongside a yield of 25.437% ±0.150%. Principal component analysis (PCA) found a sample distribution pattern into 3 clusters with a cumulative variance between PC1 and PC2 of 82.79%. These findings demonstrate that pretreatment and temperature selection critically influence dried BSFL quality, with hot water immersion and higher drying temperatures enhancing nutrient retention and process efficiency.

Keywords: bioconversion; feed processing; feed protein; organic waste treatment; sustainable agriculture

The steady rise in the global population has contributed to a corresponding increase in the production of organic waste. If not managed properly, this waste can lead to various environmental issues, including pollution, the release of greenhouse gases, and other harmful ecological effects (Kacaribu and Darwin, 2024). The recycling of agricultural waste is very important to achieve sustainable development of agriculture (Khodkam et al., 2024).

BSFL are tropical larval species that have the ability to degrade organic waste very well compared to other larvae (da Silva and Hesselberg, 2020). BSFL are able to degrade up to 80% of the amount of organic waste given (Salam et al., 2022). BSFL are able to extract energy and nutrients from vegetable waste, food waste, animal carcasses, and faeces as foodstuffs, because in their digestive system there are protease, lipase, and amylase enzymes (Chen et al., 2023). Organic waste is converted into quality protein and lipid (Larouche et al., 2019).

In Indonesia, a study related to landfills states that the waste disposed of in landfills is far more organic than inorganic waste, with a percentage of 63.82–83.21% being organic waste (Handayanta, 2010). This is a problem for the environment, but also a potential for the development of BSFL.

Indonesia has the potential to develop BSFL because it is supported by climatic conditions and the availability of organic waste raw materials as a growing medium for BSFL. BSFL has the potential as a source of cheap and easy-to-cultivate protein (Hariati et al., 2022) that also helps reduce environmental pollution from organic waste. BSFL contain antimicrobial and antifungal properties, so that when consumed fish will increase the body's resistance from bacterial and fungal attacks (Marbun et al., 2020). BSFL contain quite high nutrients, namely protein content of around 30–45% (Liu et al., 2017; Siddiqui et al., 2022). Meanwhile, according to Ardiansyah et al. (2021), BSFL contain crude protein at 35.5%, crude lipid at 12%, ash content at 11%, dry weight at 89%, calcium at 7%, extract material without nitrogen at 7%, energy metabolism at 12,287.69 $kJ \cdot kg^{-1}$, so that it can be used as a feed ingredient for fish, poultry, and livestock.

Numerous studies have identified the presence of pathogenic bacteria, including *Salmonella* spp., *Escherichia coli*, and *Bacillus cereus*, in BSFL (Kashiri et al., 2018; Wynants et al., 2019). To ensure product safety, prolong shelf life, and optimise nutritional quality, effective processing methods such as thermal pretreatment and controlled drying are essential. In this study, two pretreatments were evaluated: steaming and hot water immersion. These methods are particularly relevant for lipid-rich materials like BSFL, as thermal pretreatment facilitates lipid reduction by promoting the release of intracellular fluids during processing. The application of heat increases lipid molecular mobility, weakening intermolecular cohesion and enhancing lipid extraction efficiency (Purschke et al., 2017).

Drying is a preservation technique that employs heat energy to remove moisture from materials through evaporation, thereby reducing water activity (aw) to levels that inhibit microbial growth and enzymatic degradation. By suppressing these biological and chemical processes, drying extends shelf life while maintaining nutritional and structural integrity (Saucier et al., 2022). However, the process itself imposes stress on biological materials: cellular osmotic pressure and reactive oxygen species generated during dehydration can damage macromolecules and membrane structures, potentially altering the product's physicochemical properties.

In Indonesia, BSFL are predominantly dried using manual roasting methods, which expose larvae to extreme temperatures (140–180 °C). These conditions often degrade product quality through protein denaturation and lipid oxidation (Dortmans et al., 2017). Recent efforts to optimise BSFL drying include mechanical approaches such as rotary dryers with draft fans, though inconsistent rotation speeds risk overdrying and material adhesion to chamber walls. Similarly, electric-heated dryers face scalability challenges due to high energy demands, limiting their practicality for micro-, small-, and medium-sized enterprises (MSMEs) (Citra, 2022). Promisingly, rack-type dryers operating at 60 °C can reduce BSFL moisture content from 66% to 11% within 12 hours, though further refinement of temperature control and pretreatment methods is needed to balance efficiency with nutrient retention.

This study investigated the combined effects of thermal pretreatment (steaming vs. hot water immersion) and drying temperature (42 °C, 50 °C, 58 °C) on BSFL characteristics, including moisture content, protein and lipid preservation, ash content, and yield. By identifying optimal processing parameters, this work aimed to advance scalable, energy-efficient drying techniques tailored to the needs of Indonesian MSMEs.

Material and Methods

Raw material

The study utilised BSFL, *Hermetia illucens* L. (Diptera: Stratiomyidae), sourced from a commercial cultivation facility in Subang Regency, Indonesia. Larvae were harvested at 16–21 days post-hatching, corresponding to the late instar stage prior to pupation.

Sample preparation

Fresh BSFL were thoroughly rinsed under running water to remove debris and drained. Cleaned BSFL underwent thermal pretreatment to inactivate microorganisms and terminate larval activity using one of two methods:

1. steaming at 90–95°C,
2. immersion in hot water (90–95°C), each applied for 15 minutes.

Pretreatment duration was selected based on prior findings by Putri (2022), which demonstrated that 15-minute steaming optimises BSFL flour quality by balancing microbial reduction and nutrient preservation. This step also facilitates moisture removal during subsequent drying by disrupting cellular integrity, thereby enhancing water evaporation and lowering product water activity (a_w) for extended shelf life (Saucier et al., 2022). Following pretreatment, larvae were cooled to ambient temperature (25 °C) and evenly distributed on stainless steel trays (60.5 × 41 cm) to ensure uniform airflow. Drying was conducted in a thermostatically controlled cabinet dryer (222.5 × 95 × 65 cm) with two independent chambers (50 × 95 × 135 cm each), each containing 20 adjustable racks. The system utilised electric heating elements paired with a centrifugal blower to distribute heat evenly, while integrated thermocouples maintained temperature accuracy (±1 °C) across all replicates.

Experimental design

This study employed a Randomised Complete Block Design (RCBD) with two experimental factors:

1. drying temperature (42 °C, 50 °C, and 58 °C),
2. pretreatment method (steaming [S] vs. hot water immersion [I] for 15 minutes).

Each pretreatment-temperature combination was replicated three times, resulting in 18 experimental units. Drying temperatures were selected based on the operational limits of the cabinet dryer and preliminary trials indicating 24 hours as an efficient duration to achieve target moisture levels while avoiding thermal degradation. Pretreatment conditions were standardised to ensure microbial inactivation and structural modification of larvae prior to drying.

Yield analysis

The yield was obtained from the comparison between the dry weight of the BSFL produced and the weight of the fresh material of the BSFL. The amount of yield was obtained using Eq. (1).

$$yield = \frac{M_d}{M_f} \cdot 100\% \quad (1)$$

where: M_d – represent mass of dry BSFL (g); M_f – represent mass of fresh BSFL (g)

Determination of colour

Colour measurements were performed using a Chromameter CR 300 (Konica Minolta, Japan) and expressed in the Hunter Lab colour system, which quantifies colour attributes through three parameters: L^* (lightness), a^* (red-green axis), and b^* (blue-yellow axis). The L^* value ranges from 0 (absolute black) to 100 (pure white), representing the sample's lightness intensity. The a^* axis denotes chromaticity on a red-green scale, where positive values (0 to +100) indicate increasing redness and negative values (0 to -80) signify greenness. Similarly, the b^* axis with positive values (0 to +70) reflecting yellowness and negative values (0 to -70) corresponding to blueness (Monisha and Loganathan, 2021).

Determination of moisture content

The moisture content of BSFL was determined by drying the samples in a forced hot air oven at 105 °C for 3 hours (Lenaerts et al., 2018). After drying, the samples were placed in desiccators to reach equilibrium. The initial and final weights of the BSFL were recorded, and the moisture content was calculated using Eq. (2).

$$moisture\ content = \frac{M_f - M_d}{M_f} \cdot 100\% \tag{2}$$

Determination of ash content

Ash content was measured using the gravimetric method following the Association of Official Analytical Chemists (AOAC) method for animal feed (Thiex et al., 2012), involving ashing in a furnace at 600 °C. At this temperature, organic matter such as proteins, oils, and starches was combusted, leaving only inorganic ash residue (Hartanto, 2012). Ash content was calculated using Eq. (3).

$$ash\ content = \frac{M_a}{M_f} \cdot 100\% \tag{3}$$

where: M_a – represents mass of ash residue (g); M_f – represents mass of fresh BSFL (g)

Determination of protein content

Protein content was analysed using the DuMaster Buchi D-480 method (Serrano et al., 2013). This technique converts all organic components in the sample into nitrogen gas by combusting the sample to remove carbon and oxygen elements. The released nitrogen gas was measured using a thermal conductivity detector (TCD) in the DuMaster instrument. The measured nitrogen content was then converted to protein using the appropriate conversion factor (the Jones Factor with a value of 6.25). The formula for calculating protein content is shown in Eq. (4).

$$protein\ content = \%nitrogen \cdot \text{Jones Factor} \tag{4}$$

Determination of lipid content

Lipid content was determined using the Soxhlet extraction method (Khan et al., 2021). Samples weighing 2 g were placed in a cellulose thimble and dried to remove excess moisture. Hexane was used as the extraction solvent, and the process was conducted at 70 °C for approximately 3 hours. After extraction, the solvent was evaporated, and the remaining lipid was dried and weighed gravimetrically. Lipid content was calculated using Eq. (5).

$$lipid\ content = \frac{M_l}{M_f} \cdot 100\% \tag{5}$$

where: M_l – represents mass of the residue left in the extraction flask or lipid extracted (g); M_f – represents mass of fresh BSFL (g)

Data analysis

The data were analysed using Analysis of Variance (ANOVA) at a significance level of 0.05 to assess the treatment effects. Additionally, multivariate analysis was performed using Principal Component Analysis (PCA) to evaluate sample cluster distribution and the relationships between parameters. PCA was conducted in RStudio with the FactoMineR package (Lê et al., 2008).

Results and Discussion

Yield

Yield represents the percentage of product obtained by comparing the initial and final weights of the material, allowing the weight loss during processing to be quantified. The yield of dried BSFL subjected to various drying temperatures and pretreatments is presented in Fig. 1. The observed yields ranged from 25.4% ±0.15% to 32.45% ±1.02%. The highest yield (32.45%) was achieved with BSFL sample S at a drying temperature of 42 °C, while the lowest yield (25.4%) was recorded for BSFL sample I at 58 °C. These findings align with Purnamasari et al. (2020), who reported a yield of 36.95% when drying BSFL at temperatures between 55 °C and 75 °C. In their study, the highest yield (42.67%) was obtained at 55 °C for 24 hours, while the lowest (34%) occurred at 75 °C for 36 hours. The reduction in yield observed in our study can be attributed to material shrinkage during the drying process. This is consistent with Anwar et al. (2022), who noted that drying reduces moisture content, leading to a corresponding decrease in yield.

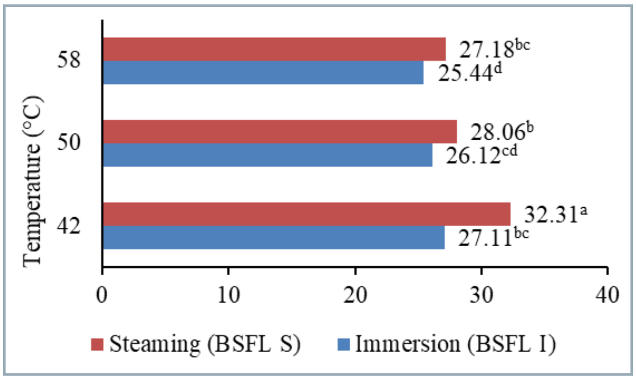

Fig. 1 BSFL yield at various drying temperatures and pretreatments
Mean values followed by different uppercase letters differed statistically by Duncan's test at a 5% level of significance; the highest to lowest values are denoted by [a] to [d], respectively

Colour properties

BSFL in their fresh state are cream in colour; after pretreatment and drying, they are blackish brown. Table 1 shows the colour properties of BSFL before and after drying, and Fig. 2 presents the results of colour properties supplemented by Duncan's post hoc test results. The BSFL I brightness value (24.03–25.454) is higher than that of BSFL S (23.903–24.010) and is slightly darker in colour, which may be due to denaturation of thermal unstable protein and Maillard browning (Monisha and Loganathan, 2021). The results of the analysis of variance showed that variations in drying temperature did not have a significant effect, while the pretreatment had a very significant effect on

Table 1 Colour properties of BSFL at various temperature variations and pretreatments

Pretreatment	Drying temperature (°C)	*L**	a*	*b**
Before drying				
Steaming	42	24.44 ±2.65	2.55 ±0.00	4.80 ±0.00
Steaming	50	23.97 ±1.19	3.09 ±0.00	4.41 ±0.00
Steaming	58	21.30 ±1.18	3.43 ±0.29	5.03 ±0.00
Immersion	42	25.74 ±1.90	3.31 ±0.00	5.87 ±0.00
Immersion	50	25.45 ±1.95	2.19 ±0.00	5.36 ±0.00
Immersion	58	24.91 ±1.56	3.68 ±0.00	6.10 ±0.00
After drying				
Steaming	42	24.01 ±1.91	2.00 ±0.37	3.82 ±0.34
Steaming	50	23.90 ±0.57	1.76 ±0.30	3.62 ±0.31
Steaming	58	25.46 ±0.64	1.67 ±0.16	3.64 ±0.31
Immersion	42	24.06 ±1.81	4.13 ±1.44	3.44 ±0.46
Immersion	50	25.12 ±0.41	2.50 ±0.51	4.44 ±0.67
Immersion	58	24.03 ±0.32	2.47 ±0.69	4.34 ±0.71

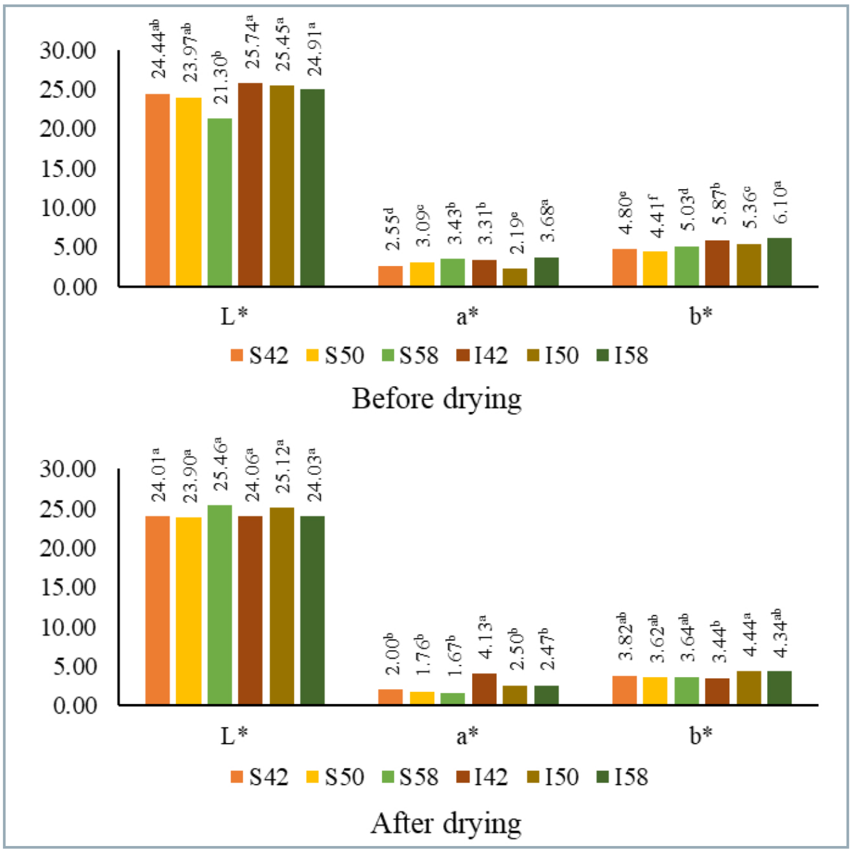

Fig. 2 Colour properties of BSFL at various temperature variations and pretreatments
Mean values followed by different uppercase letters differed statistically by Duncan's test at a 5% level of significance; the highest to lowest values are denoted by [a] to [f], respectively

the brightness value. The pretreatment of steaming and immersion in hot water causes a browning reaction in the BSFL; this occurs due to the reaction between proteins, peptides, and amino acids with the results of lipid decomposition. The heating process also causes a browning reaction (Monisha and Loganathan, 2021). The Maillard reaction is a reaction that occurs between the reactive carbonyl group of a sugar compound reacting with a nucleophilic amino group; the result is a complex mixture of molecules that produces a brownish yellow colour. The BSFL S *a** (redness) value of 1.757–1.999 is lower than that of BSFL I (2.413–2.5), although the ANOVA test results showed no significant effect. The *b** value (yellowness) in BSFL S is 3.617–3.822 and in BSFL I 4.197–4.455; this indicates that there is a number of melanin pigments (Peng et al., 2022) that inhibit yellowness in BSFL I (Ushakova et al., 2019). Meanwhile, according to Shabrina and Susanto (2017), a decrease yellowish colour was due to browning, which is the process of forming a yellow pigment which will soon turn brown due to heat treatment.

Moisture content

Moisture content is one of the most important parameters in determining the quality of a food or feed, which determines the quality and resistance of the product to damage that may occur. The higher the moisture content of a material, the greater the likelihood of damage, both as a result of internal biological activity and the entry of damaging microbes (Rezaei and VanderGheynst, 2010). Reducing the moisture content of materials through drying will result in reduced availability of water to support the life of microorganisms and also for physicochemical reactions (Rahman

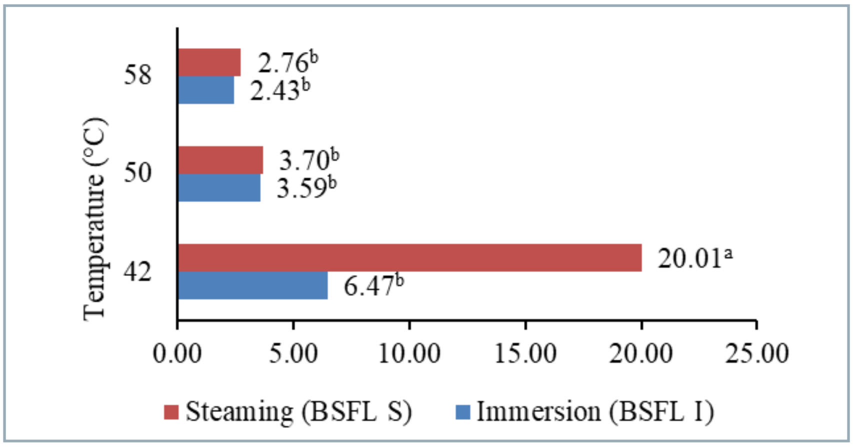

Fig. 3 BSFL moisture content at various drying temperatures and pretreatments
Mean values followed by different uppercase letters differed statistically by Duncan's test at a 5% level of significance; the highest to lowest values are denoted by [a] to [b], respectively

and Perera, 2007). Thus, the growth of microorganisms and physicochemical reactions will be inhibited, so that the product will be able to survive longer than damage.

The results of variance analysis show that the pretreatment and drying temperature variations have a very significant effect on the moisture content of BSFL. The BSFL moisture content with pretreatment and temperature variation can be seen in Fig. 3. The moisture content in BSFL S is higher than that of BSFL I. The steaming process will provide an opportunity for the BSFL material to contact and absorb more moisture, resulting in an increase in the moisture content of the material.

The highest moisture content was obtained at 42 °C steaming treatment, which was 20.010% ±3.288%, and the lowest at BSFL I at 58 °C, which was 2.427% ±0.131%, which showed it to be suitable for storage and further use. The higher the drying temperature, the lower the BSFL moisture content. This is because the higher the temperature used, the difference in water vapour content in the material and the surrounding air will be greater, leading to rapid evaporation. This is in accordance with the statement of Shabrina and Susanto (2017) that the more the drying temperature, the greater the ability of the material to release water from its surface, so that the resulting moisture content is lower.

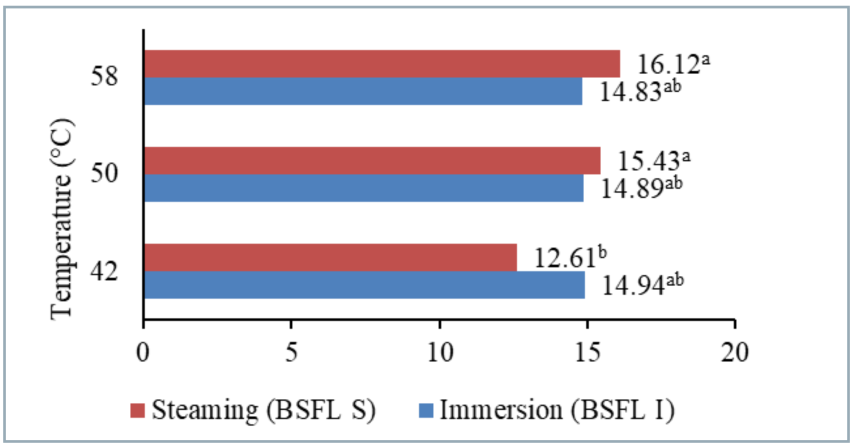

Fig. 4 BSFL ash content at various drying temperatures and pretreatment
Mean values followed by different uppercase letters differed statistically by Duncan's test at a 5% level of significance; the highest to lowest values are denoted by [a] to [b], respectively

Ash content

The results showed that the ash content after drying produced higher values compared to before drying, which ranged between 11.6% and 17.31%, and before drying ranged from 3.43% to 7.93%. This is in accordance with the results of research by Sobri et al. (2018) which states that with increasing drying temperature, ash content tends to increase due to the concentration of materials left behind. The results of variance analysis showed that the drying temperature and pretreatment did not have a significant effect on the ash content (Fig. 4).

BSFL S after drying at 58 °C produces the highest ash content value of 16.12% ±1.035%, while BSFL S at 42 °C produces the lowest ash content of 12.61% ±1.031%, as shown in Fig. 3. This is because at a temperature of 58 °C the content of BSFL water is evaporated more, so that the minerals left behind in BSFL increase. According to Purnamasari et al. (2020), the high ash content of BSFL corresponds to the high ash material of its growth media.

Protein content

The research results showed that the highest protein content was obtained at BSFL I with a drying temperature of 58 °C, which was 42.203% ±0.381%, and the lowest level obtained at BSFL S with a drying temperature of 42 °C was 35.699% ±1.032%, as shown in Fig. 5. This shows that the higher the drying temperature used will not damage the protein components but rather increase the protein components present in BSFL. This statement is consistent with the results of research by Sobri et al. (2018) that the higher the drying temperature used in foodstuffs or feedstuffs, it will increase protein levels. The use of heat in the processing of food and feed can reduce the percentage of moisture content, which results in an increased percentage of protein content. Spranghers et al. (2017) reported that BSFL protein levels are generally 33–43%. The results of research by Lestariningsih et al. (2021) showed BSFL protein content dried by roasting was 28.73%, while the research results of Purnamasari et al. (2020) indicated BSFL protein levels

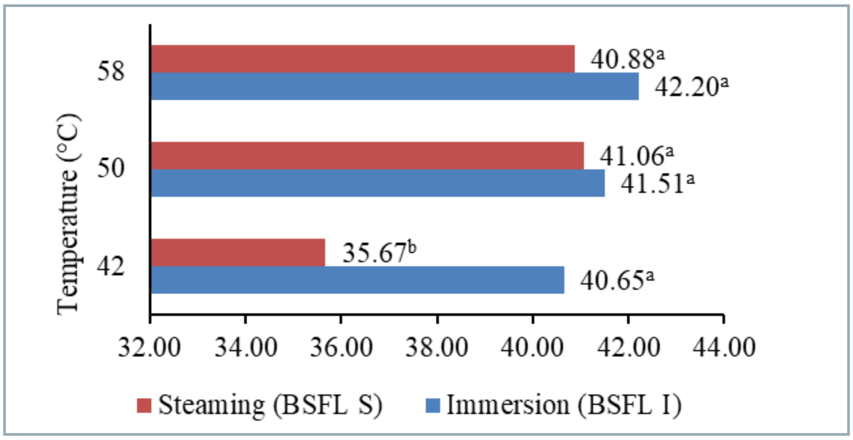

Fig. 5 BSFL protein content at various drying temperatures and pretreatment
Mean values followed by different uppercase letters differed statistically by Duncan's test at a 5% level of significance; the highest to lowest values are denoted by [a] to [b], respectively

dried at a temperature of 55–75 °C were 41.99–50.65%.

The BSFL drying process with high temperatures can cause changes in the value of the main nutrient, namely protein, due to denaturation. According to Wardhana (2016), this high protein content has the potential to replace fish meal for fish and poultry feed.

ANOVA results show that the preliminary treatment and the difference in drying temperature have a very significant effect on protein levels. Drying in general causes the Maillard reaction to occur, involving amino acids and simple sugars. According to Seyedalmoosavi et al. (2022), BSFL proteins contain amino acids, namely methionine and cysteine, similar to soybean flour. Meanwhile, according to Katayane et al. (2014), the high protein content in BSFL, one of which indicates the presence of exoskeleton components containing chitin and composed of protein.

Lipid content

The results of the variance analysis showed that the variation in drying temperature did not have a significant effect, but the pretreatment had a very significant effect on lipid content. BSFL I show higher lipid content compared to BSFL S, as shown in Fig. 6. The lipid content of BSFL S is around 24.09–29.36%, while BSFL I is 28.44–29.68%. Immersion in hot water affects enzymatic activity and causes lipid degradation, which causes the lipid value of BSFL S to decrease. According to Monisha and Loganathan (2021), lower lipid values in BSFL S indicate the occurrence of lipase hydrolysis and enzymatic denaturation, while the increase in lipid yield on BSFL I is likely to occur due to inactivation of the lipase enzyme. BSFL lipid levels contain amino acids arginine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, and valine, which are beneficial for fish feed and shrimp (Bosch et al., 2014; Sinansari and Fahmi, 2020). However, high fat content is not good for long-term product storage; therefore, lipid extraction/reduction is recommended to reduce the fat content (Toomik et al., 2024). For small-scale or farm-level operations, mechanical pressing is the most practical and safe method. For commercial or industrial-scale operations, solvent extraction or supercritical CO_2 offers higher lipid removal but requires investment and regulation compliance.

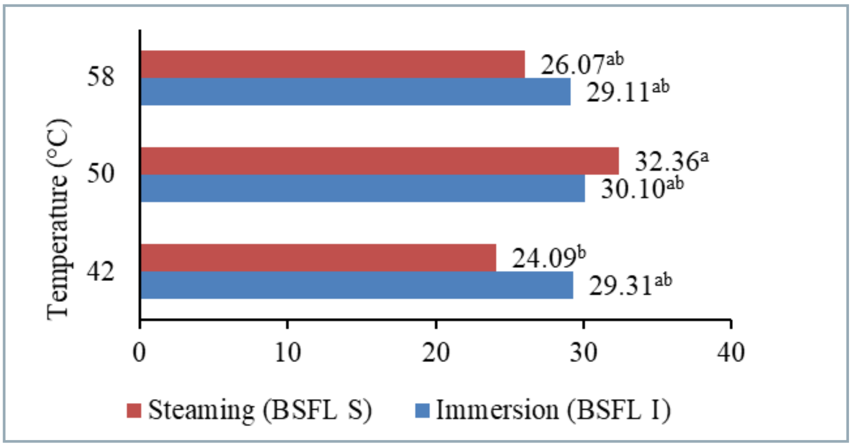

Fig. 6 BSFL lipid content at various drying temperatures and pretreatment
Mean values followed by different uppercase letters differed statistically by Duncan's test at a 5% level of significance; the highest to lowest values are denoted by [a] to [b], respectively

Multivariate analysis result

Figure 7 shows the results of the principal component analysis of six BSFL samples that are representative of each treatment variation. It can be seen that the overall data is quite representative with only two principal components (PC), where the cumulative variance of PC1 and PC2 is 82.79%. PC1 is predominantly influenced by chemical composition variables, particularly protein (21.82%), moisture content (MC) (20.78%), yield (21.40%), and ash (14.66%). This indicates that PC1 represents a dimension primarily associated with the "chemical composition" of the samples in the dataset. In contrast, colour-related variables (L^*, a^*, b^*) contribute minimally to PC1, with contributions of 1.89%, 3.28%, and 4.65%, respectively, demonstrating that colour does not play a dominant role in defining this component. PC2 reflects the colour characteristics of the samples, particularly the a^* (redness) and b^* (yellowness) values, which contribute 38.12% and 34.80%, respectively. Ash and L^* also have a moderate influence on PC2, with contributions of 14.66% and 9.11%, respectively, although their contributions are substantially lower than those of a^* and b^*. Chemical composition variables such as protein

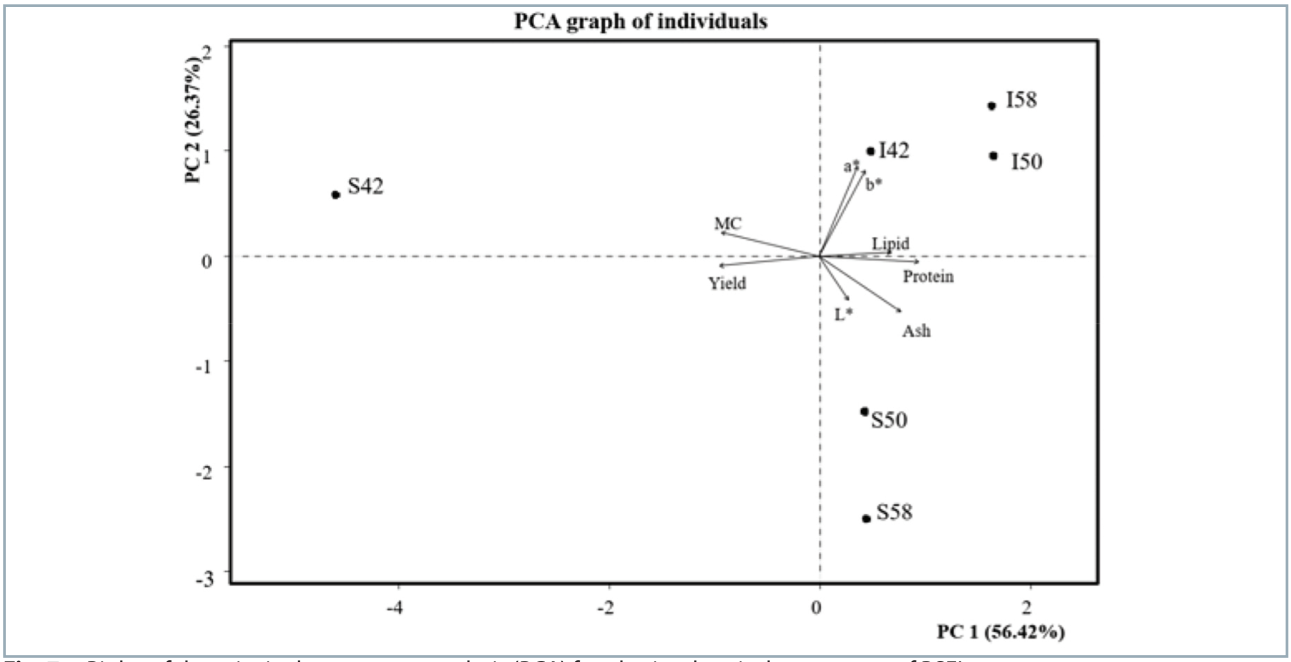

Fig. 7 Biplot of the principal component analysis (PCA) for physicochemical parameters of BSFL
MC is moisture content

(0.14%), MC (2.63%), and yield (0.45%) have minimal impact on PC2.

The interesting thing that can be seen from Fig. 7 is the distribution of samples that are divided into three clusters. The immersion treatment is grouped in one cluster with the criteria for *a**, *b**, lipid, and protein values that tend to be higher, while the steamed samples are divided into two clusters, where I42 is the cluster with the criteria for high water content and yield, whereas the S50 and S58 samples are in the same cluster as the brightness value (*L**) criteria, which tend to be high. However, it should be noted that yield is very dependent on MC, so a high yield must have a high MC. Meanwhile, the appropriate MC for this BSFL product must be minimum so that the one that best meets this criterion is an immersion sample, especially I58 which produces the highest protein and low moisture content.

Conclusion

The treatment of variations in drying temperature and pretreatment had a very significant effect on the yield, moisture content, ash content, protein, but did not significantly affect the total fat content, brightness value, colour *a**, or *b**. A drying temperature of 58 °C with pretreatment of soaking in hot water produced the highest protein content, an average of 42.203 ±0.381%, the lowest water content was 2.427 ±0.131%, ash content was 14.833 ±1.81%, lipid content was 27.18 ±2.71%, resulting in a yield of 25.437 ±0.150%. Based on the chemical and physical characteristics of BSF I, it can be used as a raw material for fish, poultry, and livestock feed; however, when using it, it needs to be treated first by extraction to reduce the lipid content. For small-scale or farm-level operations, mechanical pressing is the most practical and safe method. For commercial or industrial-scale operations, solvent extraction or supercritical CO_2 offers higher lipid removal but requires investment and regulation compliance.

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