Techno-functional analysis of insect proteins and insect-based products

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This document is part of our literature review on nutritional quality, processing, functionality and shelf life and storage of insect-based products, and the associated analytical methods.

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1. Relevance of techno-functional properties

Consumption of insects as a whole has a low acceptance in the Western world. It is therefore of great interest to process insects into nutritious powder fractions that can be used in food applications. To determine the suitability of the insect powder for dedicated food products, the analysis of techno-functional properties is necessary.

Techno-functional properties give an indication of which food products are appropriate for application of insect powders. In addition, the correlation between pre-treatments and the final (processed/extracted) powder properties can be determined. This information might be useful in modifying the functionality of the insect (usually protein) powder for different food applications. The processing/extraction conditions can be optimised based on techno-functional analysis.

The processability, texture, flavour and shelf life properties of food are controlled not only by chemical composition, but also by microstructure. Through adjusting the microstructure, the stability, texture and sensory properties of food products could be modified in function of demands (Zhao, Vázquez-Gutiérrez et al. 2016).

Elhassan, Wendin et al. (2019) refers to papers that correlate processing conditions and physical properties of mealworm in food applications. One study showed that increasing the barrel temperature during the processing of extruded insect-enriched snacks, affected the texture of the snacks. There was an inverse relationship between barrel temperature and the crunchy desirable texture of the snacks. Cooking conditions for mealworm larvae also affected their quality as food in terms of physical properties and sensory characteristics. In terms of the effect of cooking methods on sensory properties, it has been found that boiling and steaming keep the mealworm larvae similar in appearance and shape to the fresh larvae. Boiling and steaming also maintain the size of mealworm larvae better than other methods of cooking. Larvae cooked by boiling and steaming are characterized by the flavour of steamed corn, canned pupa, and boiled mushroom. The microwaving of yellow mealworm larvae leads to the highest values of some physical parameters, such as texture, hardness, and fracturability, while the highest values of adhesiveness, springiness, and chewiness had been found to be associated with boiling the larvae.

Borremans, Bußler et al. (2020) determined the effect of fermentation of mealworms on the functional properties of powders produced from the larvae. Fermentation significantly reduced the crude and soluble protein content of the non-defatted mealworm powders and in general impaired their water and oil binding, foaming- and emulsifying properties. Defatting of the powders improved most functional properties studied, except the protein solubility, water-binding capacity, foaming capacity and emulsion stability.

2. Techno-functional parameters of insect (protein) powder

Protein solubility

Protein solubility correlates with the protein quality; it is pH dependent and can be determined in the pH range of 2 to 12. The solubility of proteins is considered the most critical techno-functional characteristic since it decisively affects other functional properties such as emulsifying, foaming and gelation (Purschke, Meinlschmidt et al. 2018). Protein solubility of migratory locust protein flower ranged from 10 to 22% with its minimum and maximum at pH 5 and pH 9. The isoelectric point was found to be located at pH 4. These results are in accordance with studies reporting considerable low solubility of insect protein flours derived from mealworm larvae (3–45%; pH 2–9), black soldier fly larvae (10–35%; pH 2–9), house cricket (12–23%, pH 3–9) and tropical banded cricket (5–25%; pH 3–10), especially at weak acidic conditions (Bußler, Rumpold et al. 2016, Hall, Jones et al. 2017). When the locust flour was pre-treated by enzymatic hydrolysis, protein solubility of the hydrolysates improved over a broad pH range from initially 10–22% up to 55% at alkaline conditions. Furthermore, hydrolysis resulted in enhanced emulsifying activity (54%) at pH 7, improved foam ability (326%) at pH 3 and advanced oil binding capacity. Stone, Tanaka et al. (2019) also concluded that proteins from mealworm and cricket had low solubility (22–30%) at all pHs measured in the range of 2 to 12. They advised more research is needed into the applicability of insect proteins as ingredients in specific food products where high solubility is not a requirement, such as extruded snack products, binders in meat products, nutrition/sports bars, and bakery products.

Zhao, Vázquez-Gutiérrez et al. (2016) found that protein solubility of mealworm extract in distilled water was at a minimum between pH 4 and 5, and increased below and above this pH range. The solubility reached its highest value at pH 9. Lower solubility was observed on adding NaCl to the solution. It has been suggested that addition of NaCl could result in a shift in the isoelectric point to a more acidic pH, which could be explained by the change in charge characteristics due to ion (Cl-) binding effects.

Water and oil absorption capacity

In food applications, the water absorption capacity is related to the ability to retain water against gravity and includes bound water, hydrodynamic water, capillary water and physically entrapped water. Several functional properties (solubility, foaming, emulsification, viscosity, gelation and coagulation) can be influenced by protein-water interactions. Oil absorption capacity is mainly attributed to the physical entrapment of oil and to the number of non-polar side-chains of proteins that bind the fatty acids in the oil (Zhao, Vázquez-Gutiérrez et al. 2016).

Water and oil holding capacities are important functional properties. Water holding capacity affects texture, juiciness, taste, and most notably the shelf life of bakery products (Jideani, 2011). The ability to absorb and retain fat and to interact with it in emulsions, influences textural and sensory attributes of food (Haque, Timilsena et al. 2016).

Son, Lee et al. (2019) concluded that water and oil absorption activity are negatively influenced by the oil content of the particles of mealworm powders. Defatted powder with lower fat content had higher functionality for developing into an emulsion or foam, and its stability was also good. This observation is confirmed by Borremans, Bußler et al. (2020). Cricket powder appears to have high water absorption capacity, indicating that bakery products enriched with cricket powder can maintain good technological properties during storage (da Rosa Machado and Thys 2019). When migratory locust protein flower was enzymatic hydrolysed, water holding capacity remained unchanged, while oil-binding capacity improved (Purschke, Meinlschmidt et al. 2018).

Foaming capacity and stability

Stone, Tanaka et al. (2019) compared the foaming properties of cricket and mealworm powder with protein concentrates from yellow pea and faba bean. The pulse proteins produced more foam than the cricket protein; however, the cricket protein foam had a higher 30-min stability. The mealworm protein was non-foaming and is therefore not suitable for applications requiring foam. The lipid contents of the insect powders were much higher than the pulse proteins, which may have negatively influenced some of the functional properties of the insect proteins. Kim, Yong et al. (2020) investigated the amino acid composition and protein technical functionality extracted from three different edible insects, of which *Tenebrio molitor*. Three steps used for protein extraction were: grounding, defatting, and extraction. Through extraction steps, foam capacity and stability of Tenebrio molitor improved. The difference between insects was shown after defatting. This inhibition of foaming might be due to excess fat composition in the edible insects. According to Haber, Mishyna et al. (2019), foaming capacity was increased after defatting and alkaline states of solution increased significantly foaming capacity of extracted protein. Enzymatic hydrolysis of insect protein powder can also improve foam ability. Purschke, Meinlschmidt et al. (2018) found that hydrolysis of migratory locust protein flour improved significantly the foam ability at pH 3-5 up to 326%. A poor foaming capacity of insect proteins extracted from yellow mealworm and house cricket is also described in (Yi, Lakemond et al. 2013). The soluble protein fractions of both insects had poor foaming capacity at pH 3, 5, 7 and 10.

Gelling capacity

Gelling behaviour and its temperature dependence are important for final applications of the insect proteins and were therefore investigated. Rheological tests showed that the elastic modulus is influenced by temperature, sample concentration, salt and enzyme addition, incubation and pH alteration. Results demonstrate that the functional properties of yellow mealworm protein extract can be modified to make it suitable for different food applications (Zhao, Vázquez-Gutiérrez et al. 2016). Yi, Lakemond et al. (2013) studied techno-functional properties of five different insect species, including *Tenebrio molitor* and *Acheta domesticus*. The soluble protein fractions of all five types of insects could form gels at a concentration of 30% w/v. At a concentration of 15 % w/v at pH 7 and 10, A. domesticus supernatant formed the strongest gels among all insect species. The gelation temperature ranged from about 51 to 63 °C for all insect species at pH 7. Factors affecting the gel properties in general are pH, protein concentration, and thermal treatment.

Water activity

Generally, microbes, especially fungi, cannot grow at water activity less than 0.62–0.70 and the safe storage level is 0.65 for long-term storage (Abdullah, Nawawi et al. 2000). Mealworm powder analysed by Khuenpet et al. (2020) contained low content of water activity (0.185+0.005). Therefore, it is safe from microbiological risk for long-term storage.

Microstructure

The processability, texture, flavour and shelf life of food is controlled not only by chemical composition, but also by microstructure. By adjusting the microstructure, the stability, texture and sensory properties of food products can be modified in function of demands Zhao, Vázquez-Gutiérrez et al. (2016). With increasing pH from 7 to 13, the aggregation and particle size of proteins in mealworm powder dispersions decreased due to the increased solubility of the proteins with increasing pH. There is also a change in appearance, with the dispersions becoming clearer, brighter and more yellow with increasing pH. When the pH of dispersions was raised to 11, the aggregate structures opened and the protein solubility increased, resulting in fewer particles and a decrease in particle size. As pH was lowered back to 7, the dissolved proteins did not form aggregate structures of the same size, but resulted in smaller protein particles compared with the sample which was not adjusted to pH 11. This information might be useful in modifying the functionality of the protein extract for different food applications (Zhao, Vázquez-Gutiérrez et al. 2016).

Colour

The colour of insect powders and finished food products are determined using a colorimeter. Results are expressed as Hunter colour values of L (the lightness), a (the hue on a green (−) to the red (+) axis) and b (the hue from blue (−) to yellow (+)) (Haber, Mishyna et al. 2019). The colour values of powders are associated with their oil content.

Data suggest that the colorants of mealworms are easily soluble in oil and that powders may be brighter if lipids are further eliminated (Son, Lee at al. 2019). Some common characteristics were observed in the colour value of extracted and defatted mealworm powder (Kim, Yong et al. 2020). The lightness value decreased after the extraction process, including the redness and yellowness. The colour of the insect is generally decided by typical pigments such as melanin (Wittkopp and Beldade 2009) and sometimes the pH condition determines the colour due to protein aggregation and oxidation of colour pigment (Atkinson et al., 1973). Furthermore, according to Hillerton and Vincent (1983), tanned chitin had a higher hydrophobicity than untanned chitin and the ratio of tanned and untanned chitin can decide mechanical properties of edible insect. Therefore, colour values can be used as indicator of mechanical properties of edible insects.

Physical properties and flow properties of powders

When making and packaging powders in the food industry, the ability to be easily transported through pipes is required. Therefore, Son, Lee et al. (2019) analysed parameters related to powder flowability, such as proximate compositions, morphological characteristics, and flow properties. In summary, there were many limitations when powders were made from whole-fat mealworms. Thus, the defatting process was recommended for mealworm powder processing. When the oils were eliminated, the flowability and physicochemical properties were elevated, but consumer desirability was lowered due to its flavourlessness. Among the press-defatted mealworm powders, mealworm powder defatted with pressure and ground with a high-performance jet mill, showed the most proper characteristics for overall use.

Table 1: Overview of techno-functional analysis methods on insect powder

Analysis	Method	Reference
Colour	Colorimeter (Hunter Lab)	Khuenpet et al. (2020)
	Noncontact digital imaging system (digiEye)	Purschke et al. (2018)
	Chroma meter CM 600d Konica Minolta	Zhao et al. (2016)
	Colorimeter (CR-5, Konica Minolta)	Borrenans et al. (2020); Son et al. (2019)
	Colorimeter (CR-400, Konica Minolta)	Indriani et al. (2020); Haber et al. (2019)
Density	ISO 7971-1:2009	Purschke et al. (2018)
	Wang and Kinsella (1976)	Addapted by Borrenans et al. (2020)
Emulsion capacity	Zielinska et al. (2018)	Addapted by Borrenans et al. (2020)
	Pearce and Kinsella (1978)	Addapted by Son et al. (2019)
Flow properties	BT-1001 powder integrative tester	Son et al. (2019)
Foaming capacity	Zielinska et al. (2018)	Addapted by Borrenans et al. (2020)
	Liu et al. (2010)	Addapted by Stone et al. (2019)
	Lawhon et al. (1972)	Addapted by Son et al. (2019)
Microstructure	X-ray micrtomography	Azzollini et al. (2018)
	BT-1800 particle size analyser	Son et al. (2019)
	Nikon Eclipse Ni-U microscope	Zhao et al. (2016)
	Scanning electron microscope	Haber et al. (2019)
Particle size distribution	Sieve analysis ICC No 207	Purschke et al. (2020)
Pasting properties	Rapid Viscosimeter (Perten Instruments)	Khuenpat et al. (2020)
	Microvisco-amylograph (UNI 10872:2000)	Indriani et al. (2020)
Rheological propeties	Small amplitude oscillatory shear measurements (SAOS)	Zhao et al. (2016)
Texture Profile	Texture analyser (TA-XT Plus)	Azzollini et al. (2018); Purschke et al. (2018)
	Texture analyser (Stable Micro System)	Khuenpat et al. (2020)
Water activity	Water activity meter (Aqua lab 4 TE)	Indriani et al. (2018)
Water/Oil holding capacity	Kabirullah and Wills (1982)	Addapted by da Rosa et al. (2019)
	Cho et al. (2013)	Addapted by Son et al. (2019)
	L'Hocine et al. (2006)	Addapted by Zhao et al. (2019)

3. Techno-functional parameters of finished insect-based products

Insect powders added to food products can influence the properties of that product. The determination of the techno-functional properties of these final products is generally product-specific and/or with dedicated equipment.

Texture profile analysis (TPA)

This is the most common techno-functional property that is analysed in bakery products containing (protein) insect powder. Slices of bread, cake, etc. are subjected to a texture analyser. Hardness, springiness, and cohesiveness can be recorded from this measurement (Haber, Mishyna et al. 2019).

Haber, Mishyna et al. (2019) found there was no significant difference for texture, colour and taste parameters with the addition of grasshopper powder to a wheat bread recipe. This research shows that grasshoppers' powder can be incorporated into bake products in order to increase its nutritional value without damaging the texture and sensorial attributes. However, the concentration of the powder should be taken into consideration, because the smell parameter score decreased significantly when comparing wheat bread and 200 g/kg grasshoppers bread. 100 g/kg grasshoppers bread had similar smell parameter scores to wheat bread. The addition of larval-stage mealworm powder to bread does affect the texture, as found by Khuenpet et al. (2020). The hardness of fortified bread samples raised approximately 4 times when adding larval-stage mealworm. Dough stickiness increased with the increasing level of mealworm powder. Sticky dough is difficult to process because it will stick to the equipment surface, resulting in the decrease of bread quality. The bread product without addition of mealworm powder had the lowest hardness and chewiness values.

Breads produced with cricket powder had lower cohesiveness than other breads enriched with buckwheat or lentil. However when canola oil was removed from the formulations, a significate increase in cohesiveness was observed for the enriched breads with cricket powder. The loaves containing 10% of cricketpowder (no oil) had the highest cohesiveness from all formulations. This parameter reflects internal cohesion of the material. Therefore, breads with high cohesiveness are desirable because they are less susceptible to crumble when sliced and do not disintegrate during mastication. All of the enriched breads presented crumbs with higher hardness and chewiness than the control bread. However, for the ones enriched with cricket powder, those parameters improved after canola oil was removed from the formulations, resulting in products with similar characteristics to the control sample (da Rosa Machado and Thys 2019).

Specific volume

The addition of grasshopper powder in bread decreased the specific volume and resulted in softer texture. The specific volume value of bread enriched with grasshopper protein was lower than wheat bread, since the gluten was diluted and less starch bonds were formed. On the other hand, the texture was softer possibly because of the higher moisture content (Haber, Mishyna et al. 2019). In the study of Roncolini, Milanović et al. (2019), the addition of mealworm powder yielded an enhancement of the specific volume and a softer bread compared with the control breads. These findings can be likely described to the fat fraction of the added mealworm powder. It is known that in bread making, fat is often incorporated as an antistaling agent and volume improver. Unlike the study of Khuenpet et al. (2020) where it was found that an increase of mealworm powder leads to a lower specific volume. This phenomenon was described to be related to the gas retention ability of gluten, which has a positive correlation to the specific volume.

Cook loss and emulsion stability

When products are cooked (either at home or in a manufacturing facility), the amount of water or fat loss absorved during this thermal processing is an important factor. This property is closely related to the water absorption and the emulsion capacity of the ingredients employed in the formulation. A reduced loss of the product weight after cooking is desirable, since consumer will not accept products that present a high level of mass loss. This methodology is broadly applied in meat and meat analogue products (Álvarez, Drummond et al. 2018). In the same way, the capacity of a raw formulation to retain water can be of benefit and a similar approach to that employed for protein powders can be employed; this will provide an idea of how much water can be loss during storage and transport.

Rheological properties

There are various specific techniques to determine rheological properties of food products. Insect (protein) powders are largely tested in bread products. The batters are subjected to rheological analysis. Roncolini, Milanović et al. (2019) used dedicated devices to study physical properties of flour and flour blends such as Farinograph, alveograph and microvisco-amylograph. The addition of mealworm powder was found to negatively affect the strength of bread dough. In more detail, the higher the amount of powder added, the lower the strength of the dough was. It is likely that the reduced amount of total gluten in the blends, due to the addition of mealworm powder, influenced the gluten network formation in the doughs during mixing. Also, dough viscosity was negatively influenced. The consistency of the dough was not affected by the addition of mealworm powder.

The viscoelastic properties of cake batters can also be investigated by measuring the elastic modulus (G’) using a rheometer (Indriani, Bin Ab Karim et al. 2020). Pasting properties of flours describe the behaviour changes of flour paste viscosity along with a change in temperature, which varies mainly with their composition and characteristics of starches and proteins (Shevkani, Kaur et al. 2015). Pasting temperature indicates the minimum temperature required for flour cooking and starch gelatinization temperature (Iwe, Onyeukwu et al. 2016).

Indirani et al. (2016) studied the pasting properties of brown rice flours mixed with Bombay locust powder. Locust increment markedly changed behaviour of flour paste viscosity with decreased peak viscosity, breakdown viscosity, setback viscosity and final viscosity. Peak viscosity defines the swelling level or water-binding capacity of starch during the heating process.Breakdown viscosity will be reached when the viscosity is dropped afterwards, which indicates starch stability degree during cooking. Setback viscosity measures the tendency of starch retrogradation upon cooling of cooked starch pastes. Final viscosity indicates the viscous paste formation ability of flours upon cooling.

Pasting properties of wheat flour fortified with different levels of mealworm powder are described in Khuenpet et al. (2020). It was noticed that pasting temperature increased with the percentage of added mealworm powder whereas the peak viscosity and breakdown viscosity decreased. It might be because the proteins in mealworm powder restricted the swelling power of starch granules. Another reason may be that mealworm powder contains a high amount of fat, which can form an amylose-lipid complex when starch and lipid are heated together (Blazek and Copeland 2008).

Contrary to what was found by Indirani et al. (2016), the addition of mealworm powder resulted in the increase of final and setback viscosity. High level of final and setback viscosity indicates high level of retrogradation, which occurs at lower temperatures. Retrogradation of starch (staling of bread) is the main cause of the increase in hardness of bread products that influences the shelf life and consumer acceptance.

Microstructure

Cake made of brown rice flower, mixed with 20% of Bombay locust revealed that it had a denser structure with less porosity than the control cake. Samples showed a sponge-like structure, where the control cake had a rough crumb and open structure with more porosity from gaps and air cells. Therefore, locust powder might be a promising alternative protein source for developing protein-enriched flour and baked product, particularly cakes (Indriani et al., 2020). Azzollini, Derossi et al. (2018) analysed microstructural features of extruded cereals made of wheat flour and grinded Yellow mealworm larvae. Generally, the addition of grinded mealworms progressively reduced the size of extruded snacks, the overall porosity and the size of the pores. Also a reduction of the pore wall thickness and pore density was obtained.

Higher mealworm powder concentration in bread caused the reduction of cell density because many gas cells were coalesced into the large cell. The thickness of gas cell wall directly related to the hardness of bread. Higher concentration of mealworm powder in bread formulation produced large holes and dense crumb (Khuenpet et al. 2020). The addition of cricket powder generates bread with higher porosity in comparison with the bread enriched with buckwheat or lentil, which can be attributed to the insects' high protein and lipid content (da Rosa Machado and Thys, 2019).

Colour

Khuenpet, Pakasap et al. (2020) indicate that fortification with mealworm powder cause the colour intensity (darker colour) in bread products. Bread fortified with mealworm powder presented a reduction in lightness (L*) and yellowness (b*), while rising in redness (a*). An analogous outcome was found for the addition of cricket powder in bread. These results show that formulations enriched with dark protein sources, such as cricket and buckwheat flours, result in products with darker crumbs that can be beneficially associated to breads enriched with wholegrain flours. With respect to crumb colour, bread produced with 20% of cricket powder led to the highest variation in colour, possibly due to its low luminosity (L*) and slight tendency to red (a*) (da Rosa Machado and Thys, 2019).

4. Techno-functional properties of insect fat

Traditionally, insect oils and fats are characterised in terms of their fatty acid composition, because this determines their nutritional value. However, other chemical and physical analyses are required in order to evaluate the potential application of fats as food ingredient. For instance, crystallisation, texture analysis and solid fat content at different temperatures are required to evaluate the use of a fat as a spread, in confectionary or as an ingredient in bakery. Rheological properties help to determine spreadability, ease of cutting and stand-up in margarines (Tzompa-sosa et al., 2018). Oils and fats are the essential materials for margarine, shortening, salad oil, and other specialty or tailored products, which have become significant ingredients in food preparation or processing in homes, restaurants, or food manufacturers. The absolute viscosity of fluids is an important property needed in fluid flow and heat transfer unit operations (Diamante and Lan 2014). Triglycerides are major components of edible oils. The nature and arrangement of the fatty acids on the glycerol backbone of the triglyceride determine viscosity. Therefore, the oil viscosity has a direct relationship with degree of unsaturation and chain length of the fatty acids in lipids. Its value increases with increasing degree of saturation (Fazal et al. 2015). Limited literature has been found about the techno-functional properties of insect fat destined for food industry. Restricted to the selected insects in the Valusect project, only articles about the quality analysis of fat extracted from mealworm is summarised (Jeon, Son et al. 2016, Son, Lee et al. 2019). The effect of roasting time on the physicochemical properties and oxidative stabilities of oils extracted from mealworms (*T. molitor*) was investigated by comparting the fatty acid profile to a range of techno-functional properties. The specific gravity for unroasted mealworm oil significantly decreased after roasting. Overall specific gravity values were relatively low, compared with common vegetable oils. Reportedly, the specific gravity of oil is proportionattely influenced by the degree of unsaturated fatty acids and short chain fatty acids. Density or specific gravity of a vegetable oil depends on the type of oil and temperature. Different values of density may attribute to the difference in fatty-acid composition, total solid content and degree of unsaturation. The roasting time does not significantly affect viscosity. However, storage time does increase viscosity, regardless of roasting time (Jeon, Son et al. 2016). Bouaid, Martinez et al. (2007) reported that the viscosity of oil can increase during storage due to formation of oxygen containing molecules and oxidized polymeric compounds that cause formation of gums and sediments. The determination of iodine value and saponification value of fats and oils is very important for estimating the degree of unsaturation and average molecular weight for defining their quality. The saponification value represents the amount of potassium hydroxide required to saponify 1 g of oil (Predojević 2008). A high saponification value indicates the presence of short chain length or low Mw fatty acids. The iodine value indicates the number of double bounds (Jeon, Son et al. 2016). Roasting mealworms does not cause a significant difference between saponification values. The saponification value of mealworm oil is relatively high, compared with other oils. More than 10 min of roasting caused a significant decrease in the iodine value, compared with controls (Jeon, Son et al. 2016). A similar tendency was observed in sunflower seed oil, attributable to a reduction in the number of unsaturated sites because of oxidation and polymerization during heat treatment (Anjum, Anwar et al. 2006). Color values of mealworm oils change by roasting mealworms. In addition, the browning index significantly increases with roasting time (Jeon, Son et al. 2016). Color development is probably due to browning substances produced during the roasting process, in agreement with other thermally processed oils (Yen 1990).

Oxidative stability of insect oil is expressed by induction time, peroxide and acid value. Induction time refers to a period before the chain reaction of oil oxidation begins to accelerate. Thus, a longer induction time indicates superior oxidative stability. Unroasted mealworm oil exhibites a 10.56 h induction time. Induction times measured using the Rancimat test for other oils under identical experimental conditions were 7.65h for peanut oil and 4.40h for sunflower oil which demonstrates superior oxidative stability of mealworm oil (Jeon, Son et al. 2016). In contrast, Son, Lee et al. (2019) found that the induction time of mealworm oil was lower than that of olive oil. In the study of Farohoosh (2007), Q10 values and the oil stability index (OSI20) were calculated, that offers a prediction of shelf life of oils at 20°C, based on the induction time. When using this forecast model, the estimated shelf life of mealworm oil at 20°C was approximately 10 months.

During storage, accumulation of primary oxidation products in unroasted mealworm oil caused a rapid increase in the peroxide value. Even though roasted oils showed a significant increase in peroxide values during storage, compared to controls, increases were minor, compared to unroasted oil (Jeon, Son et al. 2016). A high peroxide value of mealworm oil was also confirmed by Son, Lee et al. (2019). They found that the peroxide value was higher than those of commercialized edible oils, suggesting that the high value of extracted oil may be a trait of the mealworm itself. The acid value is an important quality parameter of edible oils that is used to measure the content of free fatty acids. Acid values for all mealworm oils significantly increased during the first 10 days of storage. Roasting did not result in any significant differences in acid values between any oils.

Table 2: Overview of techno-functional analysis methods on insect fat

Analysis	Method	Reference
Specific gravity	American Oil Chemists' Society (AOCS) 2013 ASTMD1298 (pycnometer)	Jeon et al. (2016) Son et al. (2019)

	Horwitz, 1984	Mengistie et al. (2018)
Viscosity	Brookfield DV-IP viscometer	Jeon et al. (2016)
	Brookfield DV-IP viscometer	Son et al. (2019)
	Othman and Ngaasapa, 2010	Mengistie et al. (2018)
	Lamy Viscometer RM100	Lemuel et al. 2014
Saponification value	Jeon et al. (2016)	Jeon et al. (2016)
	Kirk and Sawyer, 1991	Mengistie et al. (2018)
Iodine value	Wijs method (1928)	Jeon et al. (2016)
Color value	colorimeter (CM-5, Konica Minolta)	Jeon et al. (2016)
	colorimeter (CM-3500d, Minolta)	Son et al. (2019)
Browning index	Jeon et al. (2016), UV-VIS spectrophotometer	Jeon et al. (2016)
Induction time	Rancimat 734, Metrohm	Jeon et al. (2016)
	Gómez-Rico et al. (2007) - Rancimat 734, Metrohm	Son et al. (2019)
Peroxide value and acid value	Jeon et al. (2016)	Jeon et al. (2016)
	Method of the Ministry of Food and Drug Safety of Korea	Son et al. (2019)
TBARS	Buege and Aust (1978)	Son et al. (2019)

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