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Original article

Studying the Thermophysical Characteristics of the Muscle Mass of the Black Soldier Fly Larvaes (Hermetia Illucens) as a Drying Object

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Abstract

Introduction. The main component of the compound feedstuff is fish meal, which has unstable quality and high price. Fish and meat-and-bone meals are replaced with protein concentrates and higher quality larvae proteins. The source of feed protein is the biomass of the black soldier flies (*Hermetia illucens*), which have a rich amino acid composition and also process food waste. The aim of the work is to study the thermal-physical characteristics of the muscle mass of the black soldier fly larvaes (*Hermetia illucens*).

Materials and Methods. The study focused on the muscle mass of black soldier fly larvaes (*Hermetia illucens*). The subject of the study is thermal-physical regularities during the drying process. The studies were conducted on the basis of Don State Technical University. The article describes determination of thermal-physical characteristics such as specific heat, thermal conductivity, moisture of the raw material, and oiliness.

Results. Heat conductivity coefficient of water 0.555 W/(m·K) for food and feed products from 0.25 to 0.40 W/(m·K) black Soldier Fly larvae have a heat conductivity equal to 0.144 W/(m·K), which is lower than conventional feedstuff components. The humidity of the examined raw material is 45% or higher while the heat conductivity remains linear and practically does not increase.

Discussion and Conclusion. The results obtained during the work can be used for parameter determination and design of various types of dryers, and for mathematical description of the dynamics and kinetics of drying.

Keywords: biomass, compound feedstuff, black soldier fly larvae, drying, specific heat, protein

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Научная статья

Исследование теплофизических характеристик мышечной массы личинок черной львинки (Hermetia illucens) как объекта сушки

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Аннотация

Введение. Основной компонент комбикорма – рыбная мука, которая имеет нестабильное качество и высокую цену. На замену рыбной, мясокостной муке приходят протеиновые концентраты, ресурсосберегающий белок более высокого качества. Источником кормового белка выступает биомасса личинок черной львинки (*Hermetia illucens*), которые обладают богатым аминокислотным составом, а также перерабатывают пищевые отходы. Цель работы – исследование теплофизических характеристик мышечной массы личинок черной львинки (*Hermetia illucens*).

Материалы и методы. Объект исследования – мышечная масса личинок черной львинки (*Hermetia illucens*). Предмет исследования – теплофизические закономерности, протекающие при сушке. Исследования проводились на базе Донского государственного технического университета. В работе описано определение теплофизических характеристик, таких как удельная теплоемкость, теплопроводность, влажность исходного сырья, масличность.

Результаты исследования. Коэффициент теплопроводности воды 0,555 Вт/(м·К) для пищевых и кормовых продуктов от 0,25 до 0,40 Вт/(м·К), мышечная масса личинок черной львинки имеет теплопроводность, равную 0,144 Вт/(м·К), что ниже, чем у привычных кормовых компонентов. Влажность исследуемого сырья 45 % и выше. Теплопроводность при этом остается линейной и практически не возрастает.

Обсуждение и заключение. Результаты, полученные в ходе работы, могут использоваться для расчета и проектирования сушилок различного типа, а также при математическом описании процесса динамики и кинетики сушки.

Ключевые слова: биомасса, комбикорм, личинки черной львинки, сушка, удельная теплоемкость, протеин

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Introduction

Fishing industry is one of the important strategic directions for ensuring world food security. The development of this industry depends on the stocks of fish food. The demand for mixed fish food is only increasing every year. In Russia, according to the Federal Agency for Fisheries, no more than 100 thousand tons of feed are produced for aquaculture, while the current needs of the industry exceed 250 thousand tons[1]. For 2021 in Russia, there were produced 4,918 tonnes of fish food that is 0.36 times less than in 2020, while global feed production according to analysts from Oil World decreased by 5% [1–4]. The decline can be caused by several factors: reduction in cereal production as a result of drought and low rainfall, environmental disasters in the oceans (oil spills, loss of a large barrier reef, etc.), reduction in the number of fish species and, subsequently, in fish meal, economic preconditions associated with an increase in the prices of processed fish food and imported fish meal. Such companies as Le Gouessant, Biomar, Coppens, Aller Aqua, Skretting are still the world leader in the production of high-value fish feed. Fish meal is the main component and, as mentioned above, production is declining. Scientists around the world have long been puzzled by this problem and the search for alternative sources of proteins other than existing ones [5–9]. Today, there is already a trend to replace meat-and-bone meal with alternative sources of protein of stable quality and environmentally friendly in the form of insect biomass. There are 1,900 species of edible insects in the world. The most common insects consumed are beetles (Coleoptera) – 31% of the total. Among the most promising species for industrial feed production are black soldier fly (*Hermetia illucens*), silkworms (*Anaphe panda*), fly (*Muca Domestica*) and mealworms (*Tenebrio molitor*). Grasshoppers (*Oxya fuscovittata*, *Acrida exaltata*, *Hieroglyphus banian*) and termites (*Trinervitermes*) are also used, but to a lesser extent [10–13].

To date, there are studies related to the addition of whole black soldier fly larvae (*Hermetia illucens*) to the diet of pigs [14; 15], the purpose of the study was to evaluate the effectiveness of introducing black soldier fly larvae (Hermetia illucens) to the diet of store pigs. The study was conducted in 2016–2017, when for feeding, there was used the dried biomass of larvaes and prepupaes of the black soldier fly (*Hermetia illucens*) in the amount of 7.0%. There was conducted a physiological experiment on 3 experimental groups of hybrid boletuses (*Sus scrofa domesticus* Erxleben) during 27 days. The results of the experiment showed a positive effect. The average daily live weight gain in the experimental group, which was fed with food with the addition of 7.0% of black soldier fly larvaes (*Hermetia illucens*), was 6.1% more compared to the control group, which was fed with a routine diet. Such a study is not a single one. In other countries, insects have long been a source of a new feed protein to be used in feeding farm animals [16; 17]. The studies also revealed a positive effect on the live weight gain of experimental groups of pigs.

However, in addition to the good results of studies in feeding pigs with the addition of black soldier fly larvaes (*Hermetia illucens*), there are studies conducted by domestic scientists N. A. Ushakova, S. V. Ponomarev, and others on the effect of new feed additives in the form of the black soldier fly larvaes (*Hermetia illucens*) when growing tilapia (cichlid family) and rainbow trout in recirculating water supply systems (RAS) [18; 19]. The results of the studies showed that the use of such a feed additive has a positive effect on the digestive tract, however, the passage of this feed increased by 35% compared to the traditional ration.

The research conducted by S. V. Ponomarev on the digestibility of chitin of the black soldier fly larvaes (*Hermetia illucens*) with valuable fish species, such as rainbow trout and sturgeon, showed that

[1] Federal Agency for Fisheries. Available at: https://clck.ru/32in5z (accessed 12.11.2022). (In Russ.)

the presence of a large amount of polysaccharides (including chitin) in the black soldier fly larvaes makes it difficult to digest feed, this because the lack of the special enzyme chitinase. In addition, chitin can negatively affect the access of proteinase to feed, and as a result, the absorption of proteins and fats decreases[2]. The chitin content in the outer skeleton (cuticle) of the black soldier fly larvaes (*Hermetia illucens*) is up to 8%. Accordingly, in order to be added to fish food, chitin must be removed, and only the inner part (muscle part) of the black soldier fly larvaes (*Hermetia illucens*) should be used. But before adding to the feed, the muscle part must be prepared, namely dried, since its moisture content can reach up to 45%, and sometimes up to 60%, depending on the substrate on which the black soldier fly larvaes (*Hermetia illucens*) were grown. Such moisture content does not allow long-term storage and use of the muscle part of the black soldier fly larvaes (*Hermetia illucens*) in feed production, so the drying process is the main task when preparing the feed component.

Protein concentrate from the black soldier fly larvaes is a good source of essential amino acids when added to a feed mixture for aquaculture [19–23]. Today, the technology for producing protein meal from insects is not publicly available and is a trade secret. Therefore, for the production of protein concentrate, a special technology was developed at the Department of Technique and Technology of Food Productions of Don State Technical University (DSTU). This technology includes a number of operations, such as separating of shell (chitin), drying of the intestines and chitin, squeezing of fat, and grinding. Drying is one of the most energy intensive processes and one of the most difficult. Due to the fact that raw materials under study are non-standard and little studied, drying process touches upon such problems as: influence of drying temperature on the quality of finished products, fat burning process [24–27], mass exchange processes, rheological properties of raw materials during drying and many others. Today, there are many ways to dry viscous material. They are microwave drying, vacuum drying, inductive drying, infrared one, etc. Choosing the drying method affects how much protein in the material can be preserved. Entoprotek Company, located in the Russian Federation, is engaged in breeding and processing the black soldier flies on an industrial scale, and produces drying with 4 different types of dryers. However, all these methods have a high degree of energy consumption of the drying process with different degree of preservation of the properties of raw materials. A promising method of drying the studied raw materials (biomass of the black soldier fly larvaes) is infrared drying [18; 28–30].

However, there are still unresolved issues related to the parameters of the drying unit and the quality of the raw materials to be dried.

The aim of the article is to study the thermophysical characteristics of the muscle mass of the black soldier fly larvaes (*Hermetia illucens*) for constructing a mathematical model of drying and for developing a drying unit.

Literature Review

The insect production and consumption industry is developing rapidly, and the demand for new products, both in pure form and as ingredients (protein concentrates, flour, fat, etc.), is increasing. Insect processing is practiced all over the

[2] Ponomarev S.V. [Study of the Digestibility of Chitin in Black Soldier Fly Larvae by Sturgeon, Trout and Tilapia]. 2018. Available at: URL: https://hermetia.ru/otchet-po-perevarivaemosti-xitina-u-ryb/ (accessed 12.11.2022). (In Russ.)

world[3] [31–33]. There are different processing technologies depending on the type of insects, but there are general principles. For example, D. Azzolini in his works considered the influence of drying regimes and hygroscopicity of meal worm larvaes (*Tenebrio molitor*) on qualitative characteristics [34]. D. Azzolini performed the blanching before air-drying at 50, 60 and 70°C, and sorption isotherms were studied after air-drying and sublimation drying. The studies resulted in moisture diffusion coefficients of D 4.85 10-11 and 1.62 10-10 m^2/s. He also described the dependencies of the Arrhenius equation, estimating at 52.1 kJ/mole. The Guggenheim – Anderson – de Bura model corresponds well to experimental data, showing type II isotherms and estimating a homogeneous layer of 0.05 gH_20/g dry matter. Scientists are engaged in processing the black soldier fly larvaes (*H. illucens*) and meal worm larvaes (*T. molitor*) into meal [35]. The purpose of the study was to study the technical and functional characteristic of the meal for the feed industry. Processing the meal worm larvaes (*T. molitor*) and black soldier fly larvaes (*H. illucens*) affected the composition, appearance, microbiological property, and the technical-functional and protein properties of the selected insect products. It was found that the direct processing of frozen or dried larvaes into meal was not feasible because of the thermally induced melting of the fat content during grinding. The results of this study show that the parameters of processing the studied insects are similar to those of processing vegetable proteins that allows the use of traditional methods of processing protein. Also to ensure microbiological safety, a combination of several physical separation methods or the use of different ways of thermal processing may be more suitable for producing protein-rich intermediate products.

Most insects are rich in irreplaceable amino acids, for example, the authors in works compared the protein content of the larva and pupa cuticles of the meal worm (*Tenebrio molitor*) [36–38]. A complete amino acid sequence has been determined for one of the pupa cuticle proteins. According to the partial amino acid sequences and the mass-spectrometric peptide card for the corresponding larval cuticular protein, it was concluded that the larval protein has the same amino acid sequence as the pupa protein. The sequence is characterized by a high content of alanine, proline, valine and tyrosine and a complete absence of acidic amino acid residues, sulfur-containing amino acids and tryptophan.

Besides to foreign experience of the use of insects for feeding, there are also researches by domestic scientists. A team of scientists from the Agrarian Scientific Center conducted a review and analysis of technologies for extruding feed and food products with the addition of insect biomass [39]. In the course of this work, there were found general regularities of extrusion process, influence of components on the appearance of products, and technological properties. The paper indicates the prospect of scientific research on the use of various insects as a feed additive for Aquacultures. Other researchers describes the positive effects of the microwave processing of dried biomass of black soldier fly larvaes before removing fat mechanically (squeezing) [40–42]. The results of the study showed a decrease in pressure in the press chamber after the microwave processing from 6 to 4.5 MPa. In addition,

[3] Official Website of LLC EcoBelok. Available at: https://hermetia.ru/kontakty/ (accessed 12.11.2022). (In Russ.) ; Official Website of Buhler. Available at: https://www.buhlergroup.com/content/buhlergroup/global/ru/industries/insect-technology.html (accessed 12.11.2022). (In Russ.)

microwave heating does not affect such an important fat indicator as the acid number. The use of microwave heating can be used not only for fat pressing, but also for pre-drying.

Scientists from Wuhan University of Technology conducted the research into the effect of convective and microwave drying methods on the nutritional value of black soldier fly larvaes (*Hermetia illucens*) [43]. The pre-prepared frozen larvaes were thawed and divided into two parts. One part was dried at 60°C in a drying oven (WGL-230B, TAISITE, Tianjin, China) to constant weight, and the other part was dried in a microwave oven (M1-211A, Midea, Guangdong, China) at 500 W for 15 minutes. Then both samples were crushed. The dried insect meal was kept at 4°C in a refrigerator and analyzed. At the same time, the drying results were presented in the form of curves divided into 3 stages, namely, that the first stage of the decomposition process was relevant with the loss of free and weakly bound water up to 150°C. The second stage of decomposition at the temperature of 150–450°C, and at this stages proteins and carbohydrates volatilized. And the third stage at the temperature of 450–550°C can be associated with the polypeptide degradation. The overall conclusion obtained during the study showed that the microwave drying did affect the amino acid composition. As a result, the proteins of black soldier fly larvaes (*Hermetia illucens*) obtained by the conventional drying (60°C) have a higher amino acid content and better digestibility that can have a positive effect when added to compound feed.

The influence of the method of preprocessing and drying on the physicochemical properties of meal worm larvaes (*Tenebrio molitor L.*) was carried out in Germany by B. Purschke [36]. The physicochemical properties of the dried larvaes have been found to be highly dependent on method of the preprocessing used. In addition to color and size, bulk material properties such as bulk density and hardness had a significant influence, resulting in different grinding behavior.

A study dealt with the influence of the convective drying and freeze drying as a mean of ensuring long-term storage [37]. Drying of whole larvaes was carried out using preprocessing, and the positive effect of preprocessing (piercing, blanching and scalding in boiling water) was proven. The time was reduced by up to 6 times when using the convective drying. It is worth noting that the study considered only the microbiological safety of the products without affecting its chemical composition.

It should be noted that preprocessing of black soldier fly larvaes (*Hermetia illucens*) before the drying process does not always have a positive effect, as evidenced by R. Bogusz's study [38]. Preprocessing with a pulsed electric field did not affect the water-binding properties of the dried insect biomass, regardless of the type of drying. Also, during the infrared drying during preprocessing, the optical properties of the biomass did not change compared to the unprocessed raw materials.

The use of insects as an alternative protein source for feed is growing exponentially. Drying is a main technological process for further processing of insect biomass. The convective drying (with hot air) is one of the most time-consuming and energy-consuming, so it is necessary to look for alternative methods, which will meet the quality of the finished product and energy consumption, and will allow improving the process kinetics.

Materials and Methods

The research was carried out in DSTU, at the department "Techniques and Technologies of Food Productions". The object of the study is the muscle part of the black soldier fly larvaes. The subject is the thermal-physical regularities of the drying process of the materials under study.

The material for the study was grown at the experimental area of the DSTU and was used as a test material as shown in Figure 1. The black soldier fly larvaes (*Hermetia illucens*) were grown on food waste (cabbage leaves, bran). Previously, the material was divided into chitin (shell) and muscle part (insides) using laboratory roller machines, then the muscle part (insides) were dried by the thermoradiation method (infrared drying) at a temperature of 100°C. For the convenience of the study, the dried material was ground in a laboratory mill (HM 310 ERKAYA) shown in Figure 2.

F i g. 1. The black soldier fly larvaes (*Hermetia illucens*)

F i g. 2. Dried muscle part of the black soldier fly larvaes (*Hermetia illucens*)

The object of the study is the black soldier fly larvaes, a species of Diptera of the family Stratiomyidae. The homeland of this species is South America, and in our regions it is grown only under certain conditions (air temperature +32°C, and air humidity of at least 80%), the fly itself is not very mobile, which makes it easier to keep, the mouthparts is weakly expressed and has a licking type. The growth and development of larvaes from laying eggs to full maturation (the larva is ready for processing) takes 32 days, while the larva grows from 19 to 27 mm per day, depending on the substrate it was grown, the nutritional value (proteins and fats) also depends on this.

The biomass of the black soldier fly larvaes includes 8 replaceable and 10 indispensable amino acids [39–41]. Most amino acids are degraded (denatured) when exposed to high temperatures. For example, collagen consisting of arginine, lysine, proline, etc., begins to break down at 65°C, but at the same time, its reactivity increases and accordingly increases digestibility. When heated to 100°C, the aromatic molecules are separated from the protein part and partially destroyed, while prolonged heating over 100°C hydrolyzes the muscle proteins, which eventually breaks down to low-molecular nitrogen compounds. There is a theory that at close to the isoelectric point the protein is denatured at low temperatures and accompanied by maximum destruction of protein molecules, but the displacement of the pH medium can increase the thermal stability of proteins [42–44]. Earlier, during the processing, namely the drying of the examined material, the similar technologies used temperatures above 100°C that does not allow speaking about the preservation of protein [45–47]. However, under the influence of temperature regimes from 60 to 100°C, it is possible to achieve maximum safety of amino acids and non-ignition of fat and exipients, which are in the raw material (biomass of black soldier fly larvaes) in large quantities [46; 48; 49].

In addition to the influence of temperature drying modes, the other important indicators are structural (mechanical) and thermophysical properties of the material, such as thermal conductivity, heat capacity, viscosity, thickness of the layer, and moisture-holding capacity of the material influence. Calculation formulas for each indicator were used to determine the thermal and physical properties of the material. Due to the fact that the fat content directly affects the drying rate and is an integral part of such parameters as heat capacity and critical humidity, this parameter must be determined as the initial characteristic of the raw material.

The specific heat capacity depends on moisture and the amount of fat. The specific heat capacity influences the temperature of the drying agent. The parameter is calculated by formula (1) [50]:

$$c = 0.1 \cdot 10^{-3}\left[(100 - W)\times (0.16M_c + 0.04\vartheta + 32.2) + 100W\right], \quad (1)$$

c – specific heat, kcal/kg·°C; W – raw material moisture, attributed to the weight of moisture in the raw material, %; M_c – oil content of raw material on absolutely dry substance, %; ϑ – raw material temperature, °C.

The humidity of the examined material was determined by a standard technique adapted to the raw material. The humidity of the biomass is determined by the adapted arbitration method according to GOST 13496.3-92. The weighting cup prepared for the study was placed in the drying cabinet for pretreatment 103°C within 30 minutes. The sample was weighed to within 1 mg. Then the samples with the analyzed mass are sent into the drying cabinet, preheated to 103°C, presented in Figure 3.

F i g. 3. Drying cabinet HORYZONT SPT-200

The drying process lasts 4 hours. The weighting cups with dried biomass are removed and cooled to room temperature, then weighed samples. Dried sample, shown in Figure 4.

F i g. 4. Dried sample of larvaes

The moisture mass fraction is determined by formula (2):

$$W_1 = \left[m_1 - \left(m_3 - m_2 \right) \right] \cdot \frac{100}{m_1}, \qquad (2)$$

where m_1 – weight bottle, g; m_2 – weight bottle, lid, g; m_3 – weight bottle, lid and the dried test sample, g.

The oil content of the raw material is determined by the Soxhlet method. The device is mounted on the round-bottomed bulb *1*, which already contains the extracting solvent (hexane was used in the study), then the refrigerator is installed *3*. In the center of the extractor *4,* there is placed a cardboard case (cartridge) *2*, in which there is 5 g of the sample between two layers of cotton wool (Fig. 5). Hexane is brought to a boiling point and, in the course of the evaporation, enters the siphon by passing through the side outlet. When the solvent fills the cavity, the substance is extracted. When hexane reaches the upper level in the siphon, it is devastated: hexane drains into the bottom round sample and the cycle repeats. The extraction time is eight hours. Next, we place the round flask with the remaining fat on the bottom in a preheated up to 105 degrees for 1 hour. After drying the flask is placed in the desiccator and then weighed. Subsequent weighing is carried out after redrying for 30 minutes. Drying and weighing shall be repeated until the difference between the two consecutive weighings is no more than 0.001 g.

Mass fraction of raw fat *X*, %, is calculated by formula (3):

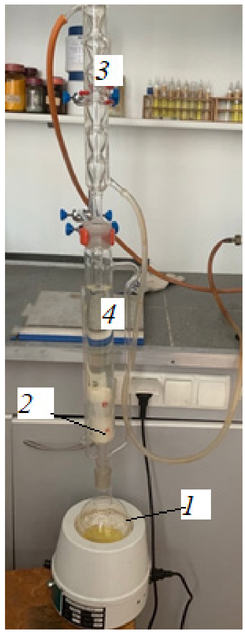
$$X = \frac{m_2 - m_1 \cdot 100}{m}, \qquad (3)$$

where m_2 – mass of flask with raw fat, g; m_1 – mass of empty flask, g; 100 – percentage conversion factor; m – sample mass, g.

Hygroscopic properties of both food and feed depend on their structure, composition, and on the temperature and humidity of the environment. The method for determining the hygroscopicity of a substance is based on the determination of the mass difference after experimental storage in a desiccator within 24 hours. The increase in mass of the test substance in percentage *X* by formula (4) shall be calculated:

$$X = \frac{m_3 - m_2}{m_2 - m_1} \cdot 100, \qquad (4)$$

where m_1 – the mass of an empty glass bottle, g; m_2 – the mass of the glass bottle with the test specimen prior to exposure in a moist environment, g; m_3 – the mass of the glass bottle with the test specimen after exposure in a moist environment, g.



F i g. 5. Soxhlet apparatus: 1 – round-bottomed flask, 2 – cartridge, 3 – refrigerator, 4 – extractor

Critical humidity is determined by analogy with the moisture content of oily vegetable raw material. The critical moisture value of the oily raw material can be calculated using formula (5):

$$W = 14.5 \cdot \left(\frac{100 - M}{100} \right), \qquad (5)$$

where 14.5 – dimensionless coefficient; M – amount of fat in the sample, %.

Thermal conductivity. The higher the humidity, the greater the thermal conductivity is. The thermal conductivity of the liquid fraction biomass is expected to be high due to the moisture content and low air content[4] [32; 51]. For this purpose, we calculate the coefficient according by the formula (6):

$$\lambda = 0.8 \cdot 10^{-6} \cdot \left(\frac{100w}{100 - w} + 125 \right) \times \times \left(\frac{\vartheta \cdot \rho}{273} + \rho + 225 \right), \qquad (6)$$

ρ – bulk mass or density, kg/m^3; w – raw material moisture, attributed to the weight of moisture in the raw material, %; ϑ – raw material temperature (20°C), °C.

The thermal conductivity coefficient determines inertial properties of both a layer and single structural oily molecules. The higher the coefficient, the faster are the heating processes during drying[5] [52–55]. Formula (7) determines this parameter:

$$\alpha = \frac{\lambda}{c \cdot \rho}, \qquad (7)$$

ρ – bulk mass or density, kg/m^3; w – thermal conductivity calculated by formula (6); c – specific heat capacity calculated according to formula (1).

Bulk density ρ_0 depends on the type, dimension and humidity. When determining this characteristic, humidity, raw material dimensions and geometric dimensions of the measuring container should be specified.

Laboratory equipment used in the study:

– laboratory analytical scales LV 210-A of the 2nd class of accuracy, error not more than 0.0001 g;

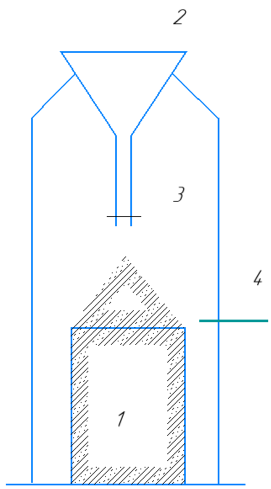
– measuring cylinder, volume 0.0001 m^2;

– metal ruler;

– screen with cell width 1, 2, 5 mm;

– standard truncated cone funnel.

Prior to testing, a pre-weighed measuring cylinder should be installed under the tube. The distance between the upper edge of the cylinder and the valve shall be 50 mm (Fig. 6). The material must be pre-dried and weighed.



F i g. 6. Flow chart of bulk density instrument: 1 – measuring cylinder; 2 – truncated cone funnel; 3 – valve; 4 – material equalisation location

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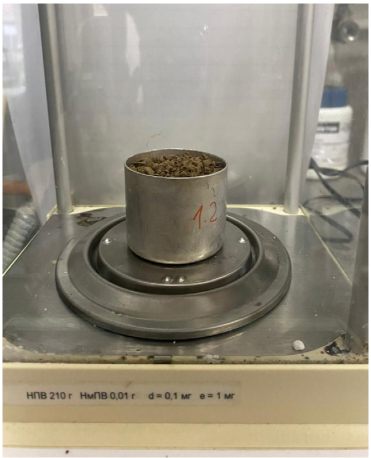
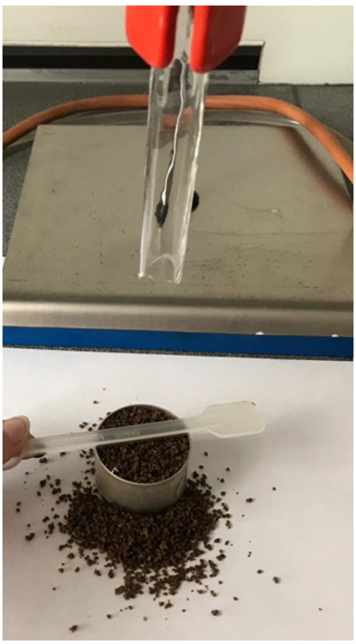
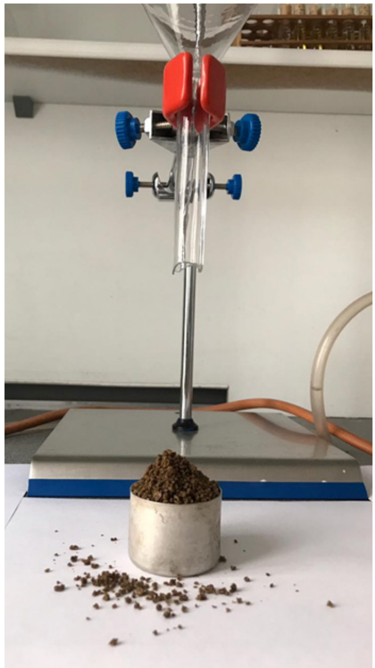
The dry material is poured into the funnel, then the valve is opened, the cylinder is filled with excess, the bolt is closed and the excess material is cut off from the middle to both sides with a metal ruler on a level with the cylinder edges. The material may not be compacted (Fig. 7–9). The cylinder with the material is then weighed within to 1 g. The tests are carried out in 3 repeats.



F i g. 7. Weighing of the test sample



F i g. 8. Levelling for better installation



F i g. 9. Biomass in a dimensional cylinder

Bulk density is defined as the ratio of the mass of a product to the volume of a dimensional container, according to the formula (8):

$$\rho_0 = \frac{m - m_{con}}{V}, \tag{8}$$

where m – mass of material tested and measuring capacity; m_{con} – tarra mass; V – dimensional capacity.

The arithmetic mean of the results of 3 parallel definitions is taken as the test result.

Statistical analysis

All experiments were repeated three times and each used a new batch of larval samples for independent testing. Experimental results were expressed as mean ± standard deviation. The data from all replicates were analyzed using the statistical program Statistica 10.0 followed by one-way analysis of variance with a significance level of 0.05.

Results

Thermal properties of both food and feed products were assessed in the section Materials and Methods, the results of the obtained studies were summarized in table for ease of presentation.

Table

Research results

Indicator	Value	Unit of measure
Raw material moisture	45	%
Critical humidity	9.5	%
Thermal conductivity coefficient	0.00055	m^2/s
Coefficient of thermal conductivity	0.144	W/(m·K)
Hygroscopic	7.14	%
Specific heat	0.429	kcal/kg°C
Raw fat content	51.45	%
Bulk density	605	kg/m^3
Specific volume	1.652	cm^3/g

Knowing the regularity of heat and moisture movement, it is possible to draw conclusions about the appropriateness of the use of infrared drying method, and the amount of energy spent for the drying process. These properties determine the parameters and modes of the drying process and the design of the working body.

The coefficient of thermal conductivity determines how much heat passes through the unit of the surface area of the raw material into a unit of time at a temperature gradient equal to one. This indicator influences the correctness of the location of the working body (IR emitter) when forming the direction of heat flow. The thermal conductivity of water is 0.555 W/(m·K) for food and feed products from 0.25 to 0.40 W/(m·K), and the muscle mass of black soldier fly larvaes is 0.144, which is lower than that of conventional feed components. The humidity of the material has a significant influence on the thermal conductivity of the entire raw material, so at high humidity the investigated raw material has a humidity of 45% and above, the thermal conductivity remains linear and practically does not increase[6] [53; 54]. However, if we consider the specific heat capacity of the dried material, we observe an inverse pattern, the higher the humidity, the higher the coefficient of thermal conductivity, as confirmed also by studies[7] [57]. In accordance with the universal physical principle by Le Chateller-Brown, the stronger the external influence on the treatment object at the initial moment, the more intense are the internal processes that seek to return the system to a state of equilibrium. The obtained coefficients are theoretically calculated. Further experimental studies are needed to fully confirm the hypothesis.

Discussion and Conclusion

The study conducted to determine the heat-physical characteristics of the muscle mass of the black soldier fly larvaes (*Hermetia illucens*) showed that the processes associated with heat processing are typical non-stationary and irreversible ones, for which the principles of thermodynamics of irreversible processes and first of all the principle of linearity are applicable. The increasing of the driving forces of the process has certain technological limits

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(maximum permissible gradients of temperature, moisture content, pressure, etc.), while in increasing the kinetic coefficients (which include the above thermal and mass exchange characteristics) there are significant reserves. The results of the study are recommended to be used in the development of a mathematical model for drying of the highly wet oily raw material, which is the muscle mass of the black soldier fly larvaes[8] [57–63].

In view of the diversity of literary sources, such studies were not found, which determines the relevance of the studies. However, the results of the experiment require further research.

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