http://doi.org/10.35784/iapgos.7322

received: 22.02.2025 | revised: 22.07.2025 | accepted: 18.11.2025 | available online: 20.12.2025

MECHANICAL FRACTURE ENERGY AND STRUCTURAL-MECHANICAL PROPERTIES OF MEAT SNACKS WITH BEEKEEPING ADDITIVES

Artem Antoniv[1], Igor Palamarchuk[2], Leonora Adamchuk[3], Marija Zheplinska[2]

[1]Independent Research Institute "Ukrainian Science Hub", Brovary, Ukraine, [2]National University of Life and Environmental Sciences of Ukraine, Department Processes and Equipment of Agricultural Production Processing, Kyiv, Ukraine, [3]Institute of Veterinary Medicine of the NAAS of Ukraine, Department of Bee Diseases, Kyiv, Ukraine

Abstract. *The choice of an effective technological scheme of food production is mainly determined by the need to meet consumer needs, healthy eating requirements, compliance with environmental trends, energy efficiency of the main processes of the technology used. The technology of meat chicken snacks with the addition of such biologically active additives as honey, propolis and bee pollen allows you to meet these factors due to the convenience of consumption, high protein content, ease of storage and preparation. The addition of bee pollen allows you to increase the nutritional value of the product and classify it as a health product. The tests were based on the hypothesis that when the product is destroyed, the force applied to cut the sample is proportional to the structural resistance and energy parameters, which allow you to assess the quality characteristics of snacks through the tenderness or hardness of the finished product. Experimental studies of the force and energy processes of chicken snack processing were carried out separately for a control sample of chicken fillet and spices and samples with a developed recipe, in which, together with the meat base, such beekeeping products as honey, propolis aqueous extract and bee pollen were added. The experiments were conducted to understand the behavior of the product under load, which is important for assessing their quality, safety, as well as adjusting the production processes of meat snacks to ensure high resistance to mechanical loads in practical application conditions. In general, all used samples of meat snacks with beekeeping products demonstrated effective mechanical properties as for the use of a food product; the determined parameters of the critical strength limit allow avoiding structural failure modes under excessive loads. The research results provide opportunities to optimize formulations, justify operating modes to prevent premature material failure under load, improve the structure and efficiency of technological processes based on minimizing energy consumption, preserving structural properties, improving the quality of finished products, and increasing their competitiveness in the market.*

Keywords: grinding processes, cutting work, shear stress, food structure

ENERGIA PĘKANIA MECHANICZNEGO I WŁAŚCIWOŚCI STRUKTURALNO-MECHANICZNE PRZEKĄSEK MIĘSNYCH Z DODATKIEM PRODUKTÓW PSZCZELICH

Streszczenie. *Wybór efektywnego schematu technologicznego produkcji żywności jest determinowany głównie potrzebą zaspokojenia potrzeb konsumentów, wymogami zdrowego odżywiania, zgodnością z trendami środowiskowymi, efektywnością energetyczną głównych procesów stosowanej technologii. Technologia mięsnych przekąsek z kurczaka z dodatkiem takich biologicznie aktywnych dodatków jak miód, propolis i pyłek pszczeli pozwala spełnić te czynniki ze względu na wygodę spożycia, wysoką zawartość białka, łatwość przechowywania i przygotowania. Dodatek pyłku pszczelego pozwala zwiększyć wartość odżywczą produktu i zaklasyfikować go jako produkt zdrowotny. Badania oparto na hipotezie, że gdy produkt ulega zniszczeniu, siła przyłożona do przecięcia próbki jest proporcjonalna do parametrów wytrzymałości strukturalnej i energetycznej, co pozwala ocenić cechy jakościowe przekąsek poprzez kruchość lub twardość gotowego produktu. Badania eksperymentalne procesów siłowych i energetycznych przetwarzania przekąsek z kurczaka przeprowadzono oddzielnie dla próby kontrolnej fileta z kurczaka i przypraw oraz próbek o opracowanej recepturze, w której wraz z bazą mięsną dodano takie produkty pszczelarskie jak miód, wodny ekstrakt propolisu i pyłek pszczeli. Eksperymenty przeprowadzono w celu zrozumienia zachowania się produktu pod obciążeniem, co jest ważne dla oceny jego jakości, bezpieczeństwa, a także dostosowania procesów produkcyjnych przekąsek mięsnych w celu zapewnienia wysokiej odporności na obciążenia mechaniczne w warunkach praktycznego zastosowania. Ogólnie rzecz biorąc, wszystkie użyte próbki przekąsek mięsnych z produktami pszczelarskimi wykazały skuteczne właściwości mechaniczne, jak na zastosowanie produktu spożywczego; wyznaczone parametry krytycznej granicy wytrzymałości pozwalają uniknąć trybów uszkodzeń konstrukcyjnych pod nadmiernymi obciążeniami. Wyniki badań dają możliwości optymalizacji formulacji, uzasadnienia trybów pracy w celu zapobiegania przedwczesnemu uszkodzeniu materiału pod obciążeniem, poprawy struktury i wydajności procesów technologicznych w oparciu o minimalizację zużycia energii, zachowanie właściwości konstrukcyjnych, poprawę jakości gotowych produktów i zwiększenie ich konkurencyjności na rynku.*

Słowa kluczowe: procesy szlifowania, prace skrawające, naprężenia ścinające, struktura żywności

Introduction

The efficiency of production, especially in the food industry, depends on meeting consumer needs, compliance with environmental trends and energy efficiency of production processes. The technology of meat snacks with the addition of biologically active additives, such as bee products, can meet these factors [1]. Meat snacks are convenient, high-protein products that do not require additional storage or cooking conditions. The addition of bee pollen makes it possible to increase the nutritional value of the product and classify it as a health product. To ensure the efficiency of this technology, special attention must be paid to key production stages, such as pickling and drying, which determine not only the quality of the finished product, but also its cost. The processes of mixing loose ingredients in the conditions of the created vibro-fluidized layer of material, the use of combined convective and thermo-radiative drying create prospects for a significant reduction in energy consumption while ensuring the intensification of heat exchange and diffusion. The specified technology and means of improving its characteristics shorten the process of producing meat snacks by 1.5–2 times and require less involvement of resources and equipment [13].

The production of meat snacks using functional ingredients, such as honey, bee pollen and propolis, opens up new prospects for creating high-quality products with increased biological value. However, the introduction of such innovative components into technological processes requires a detailed analysis of the impact on the structural, organoleptic properties of the product and energy consumption. Determining the main physical and mechanical properties of the product allows you to assess the characteristics of the structural destruction of the product, which makes it possible to assess the energetics of the process, the patterns of changes in the resistance of the product mass and justify the operating modes of processing. The results of the study will contribute to the development of scientifically based recommendations for the implementation of energy-efficient technologies in the food industry.

1. Literature review

The meat snack industry is mainly focused on improving the quality and consistency of traditional meat snacks or introducing new products with improved nutritional value, functional properties, more convenient packaging and improved sensory characteristics [10].

For the production of chicken sticks, researchers [5] used processes such as steaming, drying and frying. Sensory evaluation of chicken sticks was used to standardize the optimal fiber content, which was additionally added during production. The developed chicken and dietary fiber snacks increase the nutritional value, amino acid content and improve the aroma and taste [20]. Another type of meat snacks are crispy bread snacks containing chicken meat and chicken meat powder. The study [2] focused on the production of dried snacks enriched with protein. Additionally, the authors found that the hardness of the snacks was significantly affected by the type of chicken meat. Thus, the hardness was higher for samples with the addition of fresh chicken meat than for samples with the addition of chicken meat powder. As scientists note [11], meat trimmings are considered a valuable protein product obtained after the separation of meat during slaughter. They developed beef meat snacks, which were obtained through the process of heat treatment at a temperature of 150°C for 20 minutes. As a result, high physicochemical properties, texture and sensory profile of beef snacks were obtained.

Polish scientists [19] compared samples of dried meat made from the same type of muscle of ostrich, beef, and broiler chicken. It was found that meat snacks from ostrich, beef, and chicken are characterized by a high content of nutrients, including protein, minerals (the content of heme iron in ostrich is higher than in beef) and biologically active peptides (the highest content of carnosine in beef, anserine in ostrich). The content of n-3 fatty acids varies between species. Dried ostrich meat contained four times more fat than beef, while dried chicken meat contained only half this amount. In their studies, the authors [6] were concerned with creating healthy and convenient ready-to-eat snacks with increased nutritional value using chicken waste, dietary fiber, and simple processing methods. The product is designed to be shelf stable and easy to use by local populations. Adding chicken waste, a relatively inexpensive but rich source of protein, to ready-to-eat products (snacks) is an effective way to overcome protein deficiency, and the addition of dietary fiber further extends the functionality of the product.

The food industry, which most industries use, mostly exhaustible resources for its operation and adds CO_2 to the atmosphere. Accordingly, the focus is now shifting towards the installation and implementation of various energy-efficient devices and strategies, which is also confirmed by the authors' data [15].

According to the authors [4], in recent years, attention has been focused on the implementation of environmentally friendly food technologies and the awareness of their impact on the health and well-being of consumers is growing. Accordingly, new technological solutions are being used for drying processes, both thermal and non-thermal, during the production of healthy snacks. In particular, the combination of hybrid drying methods using microwaves, infrared radiation, ultrasound and vacuum effectively reduces drying time and maintains high nutritional value. Chinese scientists [21] produced dried chicken breast meat using four drying methods: hot air drying, catalytic infrared drying, electric infrared drying and drying in an electric oven. The results showed that catalytic infrared drying and electric oven drying gave the best color tone of the final product, while electric infrared drying treatment gave the highest degree of denaturation of chicken breast protein. Regarding chemical properties, the higher content of malondialdehyde in catalytic infrared drying and electric infrared drying indicated higher fat oxidation in chicken meat, which was also associated with an increased content of free fatty acids.

In some Asian countries, sand-frying techniques are widely used by street food vendors, villagers and artisanal enterprises to produce various value-added food products from various cereals, millets and pulses [8]. Sand-frying and sand-baking are gaining increasing importance as low-cost, efficient, oil-free and healthy cooking methods. However, further research is needed on the availability of micronutrients and the development of functional food products for people suffering from eating disorders. In addition, the level of residual silica and harsh working conditions require the development of energy-efficient, high-performance technologies such as continuous frying, microwave frying and fluidized bed frying. To characterize the thermal drying process of goat meat, the authors [3] applied mathematical modelling methods of convective drying kinetics and validated them with experimental data obtained from a drying tunnel. The proposed mathematical models reflected the drying kinetics with an accurate fit of the experimental data with standard errors in the range of 0.004–0.029, which allows planning the production process with high accuracy.

Depending on the protein system, pressure, temperature and duration of pressure treatment, meat can become soft, tender or tough or hard. The change in muscle texture due to heat treatment occurs due to the breaking of hydrogen bonds, while the changes due to pressure treatment occur due to the breaking of hydrophobic and electrostatic interactions. As scientists indicate [16], juiciness, elasticity and chewability are improved by high hydrostatic pressure treatment. Pre-treatment under high hydrostatic pressure softens meat, but the softening effect after high hydrostatic pressure treatment can only be measured with a combination of pressure treatment and heat treatment. The author [17] compared the structural behavior of globular and fibrous proteins during heating and found that the former expand and the latter contract. As indicated by the author, most sarcoplasmic reticulum proteins coagulate at temperatures of 40–60°C, but some coagulate up to 90°C. The spatial arrangement of fibers is of great importance for the textural behavior of meat. In whole meat, a crack that breaks the meat must pass through channels filled with liquid at temperatures below 55°C, so the fracture energy will be dissipated in the form of a viscous flow and it is considered tough. Scientists [18] have proven that the addition of soluble dietary fibers to meat products for technical and health purposes has different effects on their texture. Some dietary fibers reduce stiffness, while others increase it. For example, two forms of pectin (low-methoxylated and high-methoxylated) have different effects on texture. In addition, factors that also affect the structural and mechanical properties of meat are age, sex, and type of meat. Also, research [14] showed that nutritional supplements when feeding chickens in the form of propolis and bee pollen have a significant positive effect on the quality of chicken meat, in particular on the structural properties of meat, the colour of skin and muscle tissue, and increased carcass yield.

In general, bee pollen contains niacin, biotin, thiamine, carotenoid pigments, polyphenols, phytosterols, enzymes and coenzymes. Therefore, it is considered an ingredient with nutraceutical and therapeutic properties for healthy food [9]. Propolis is valued in the food industry for its antioxidant and antimicrobial properties against Listeria innocua and Staphylococcus aureus [12]. Honey is known for its nutritional value and preventive effect. However, recent studies [7] consider the main advantage of honey as an ingredient in health food to be its prebiotic effect due to its complex biochemical composition. Therefore, the addition of beekeeping products has a positive effect on the biochemical properties of food products. However, their effect on the structural and mechanical properties of finished products, in particular meat snacks, has not been sufficiently studied.

2. Problem statement

The modern food industry is faced with the need to ensure high product quality and reduce energy consumption for its production. In the context of the production of meat snacks, numerous challenges arise related to the optimization of technological processes, which must take into account both the preservation of the organoleptic and structural properties of the product and energy efficiency. The use of biologically active additives, such as honey, bee pollen and propolis, opens up new opportunities for improving the functional properties of meat snacks. However, their inclusion in the recipe requires a thorough study of the impact on technological parameters, changes in physical and mechanical properties, especially during the implementation of key production stages, in particular, the preparation of raw materials, pickling and drying of semi-finished products and products.

Among the presented problems, difficulties are noted in determining and assessing the energy parameters of combined processes of mechanical, thermal and diffusion processing of a product mass that is quite complex in terms of its mechanical state. The complexity of the research is added when using various additives to the main structural components of the product, the effect of which is insufficiently studied in food technologies, in particular, when using beekeeping products in the production of meat snacks. Solving these problems requires experimental research and theoretical substantiation of the driving forces of processing processes, which will allow working out clear recommendations for optimizing technological parameters and developing energy-efficient technologies in the food industry. These aspects significantly influence and determine the structure and choice of the main levers of the technological scheme for the production of meat snacks with the addition of honey, bee pollen and propolis. The perfection of the latter is determined, respectively, by both improving product quality and minimizing energy consumption for the implementation of production processes; which justifies the relevance of the research presented in this scientific work.

3. The purpose of the study

To assess the quality characteristics of chicken meat snacks with the addition of honey, bee pollen and propolis by analyzing the change in the physical and mechanical characteristics of the product mass, experimental determination of the force parameters of the destruction processes of product samples.

4. Materials and methods

The information materials during the research were scientometric and abstract databases. The research was conducted at the Institute of Plant and Environmental Sciences Slovak University of Agriculture in Nitra and the National University of Life Resources and Environmental Management of Ukraine within the framework of the project "Use of bee pollen and other biologically active products of beekeeping in the creation of healthy meat snacks with a long shelf life" during October-December 2024.

The developed technology of meat snacks with bee venom includes the following processes: preparation of the main raw materials and auxiliary components (spices, materials), salting and ripening of the meat semi-finished product (if necessary, freezing it), cutting the meat of the required shape and thickness, drying or curing, if necessary, additional surface glazing or breading, standardization of moisture content, cooling, as well as packaging, labeling and storage. The main stages of this technology are the preparation of chicken fillet and beekeeping products, cutting the meat, mixing the additives until homogeneous, marinating the meat, convective drying at variable temperatures (from higher to lower), cooling and further control of the finished snacks, packaging, labeling and storage.

Structural and mechanical properties, namely shear force and cutting work, were determined on a SANS SMT2000 universal testing machine, model 2503, which allows for the determination of specific properties through constant measurement and registration of the load arising from the resistance of the sample to mechanical action. The product sample was placed on a frame that was stationary and centered to the nozzle. Then the traverse movement was started and the data obtained was recorded by a computer. The shear force and cutting work indicators were determined on an Instron universal testing machine. All mathematical calculations for calculating the indicators and graphical processing of the results were performed using the Power Test_DOOE software. The shear force and cutting work indicators were determined using the Warner-Bratzler nozzle. Considering that the standard width of the sample should be 5 cm and the height 1 cm, the sample was cut out and measured with a ruler, the obtained data was entered into the program and recalculated according to the measured data.

The optimal ratio of ingredients was determined experimentally.

Studies were conducted using different proportions of chicken fillet, honey, aqueous propolis extract, and bee pollen to identify the most favorable combination that would ensure a pleasant, balanced taste without the dominance of any single ingredient, a soft chewable texture that remains sufficiently dense for convenient consumption, and high biological value with an optimal content of proteins, fats, and carbohydrates. A comparison of ingredient ratios for the production of meat snacks enriched with honey, propolis, and bee pollen is presented in Table 1. Commercially available chicken snacks served as the control.

In the production of meat snacks, honey was used in its liquid state. In cases where crystallization occurred, the honey was first subjected to decrystallization in a water bath at a temperature not exceeding 40°C until a uniform consistency was achieved. Propolis was used in the form of an aqueous extract with a concentration of 20%. Bee pollen was used in its natural granulated form after preliminary drying.

The raw materials must comply with both national and international standards, in particular: Directive 2001/110/EC of 20 December 2001 relating to honey; Regulation (EC) No 1333/2008 of the European Parliament and of the Council of 16 December 2008 on food additives; Regulation (EU) No 1169/2011 of the European Parliament and of the Council of 25 October 2011 on the provision of food information to consumers; Regulation (EC) No 853/2004 of the European Parliament and of the Council of 29 April 2004 laying down specific hygiene rules for food of animal origin and Commission Regulation (EC) No 2073/2005 of 15 November 2005 on microbiological criteria for foodstuffs.

Table 1. Ingredient ratios for the production of meat snacks with honey, propolis, and bee pollen

Raw material name	Raw materials per 100 kg of finished product, %			
	control sample	prototype		
		1	2	3
Chicken fillet	91.88	91.35	84.35	89.35
Sunflower honey	–	2.00	5.00	3.00
Aqueous extract of propolis	–	0.86	1.86	0.46
Bee pollen	–	0.43	0.68	0.78
Salt	1.8	1.29	2.03	1.85
Ground black pepper	0.02	0.06	0.21	0.29
Soy sauce	6.3	4.01	5.87	4.27
Total	100	100.00	100.00	100.00

Table 2. Recipe for meat snacks

Raw material name	Raw materials, kg per 100 kg of finished product	
	without added beekeeping products	with the addition of beekeeping products
Chicken fillet	306.263	290.0
Sunflower honey	–	6.4
Aqueous extract of propolis	–	2.7
Bee pollen	–	1.4
Soy sauce	20.999	12.7
Salt	5.999	4.1
Ground black pepper	0.066	0.2
Total	333.327	317.5

Sample 1 contains the highest proportion of chicken fillet (91.35%), which enhances the protein value of the product. The use of honey (2.0%), aqueous propolis extract (0.86%), and bee pollen (0.43%) is well balanced, contributing both to the sensory profile and the functional properties of the snack. The low content of salt and soy sauce reduces the risk of flavor oversaturation. Sample 2 has a lower chicken fillet content (84.35%) and a higher content of honey (5.0%) and salt (2.03%), which results in an overloaded flavor profile. Additionally, it contains the highest amount of soy sauce (5.87%) among all three samples, making the final product notably salty. Sample 3 shows a balanced ratio of ingredients overall; however, the low level of propolis extract (0.46%) does not provide the necessary functional properties compared to sample 1.

For further research, food products produced according to the recipe were used (Table 2).

5. Research results and discussion

To substantiate the technological parameters of the production of meat snacks with the addition of bee pollen, which is necessary when forming working modes of processing, the main physical and mechanical properties of the product mass were investigated. The structural and mechanical properties of many meat products are often evaluated by such concepts as "tenderness" and "consistency". However, tenderness can be assessed objectively if the most characteristic types of deformations to which the product is subjected during chewing are selected. For this purpose, shear fracture deformation is successfully used.

The main hypothesis of the conducted research is the proportionality between the force parameters of shear fracture, energy costs for the process and structural resistance of the material, expressed in the tenderness or rigidity of the product, which serve as quality criteria for the studied chicken snacks.

Structural and mechanical properties of the meat base of chicken snacks. Snacks for the study were used under different storage conditions: 1 day at a temperature of +23…+25ºC. For almost all samples, there are three characteristic areas of shear stress change (Fig. 1). From the results obtained, when the external load is increased by 30%, there is an increase in the external resistance of the material at the depth of wave propagation to a depth of 8…10 mm. This indicates the initial stage of the material's resistance to deformation, where the material actively resists the applied force.

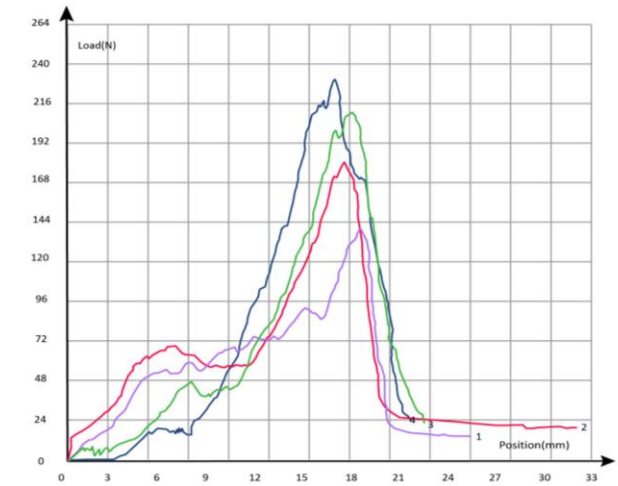

Fig. 1. Structural and mechanical properties of meat snacks without the addition of beekeeping products with a shelf life of 1 day

When the load is distributed in the material depth range from 8 to 15 mm, the shear stress remains nearly constant. This suggests that the material has entered a phase of equilibrium resistance, during which its internal structure adapts to the applied load, allowing shear to propagate without substantial variation in internal resistance.

There is an onset of resonant oscillations of the shear stress to values of 1.13 to 3.7 MPa for different samples, the amplitude value of the material resistance corresponds to 24…26 mm and a sharp decrease after 4 mm of the sample array to their end. This phenomenon is explained by the structural destruction of the material at this depth, where the material loses its integrity and ability to resist further loading.

Such a course can be explained by the structural destruction of the material already at the end of the sample array. For the production of meat snacks, it is important to take into account these stages of mechanical loading to ensure the quality and stability of the product. Optimization of the formulation and relevant technological processes can help improve the structural strength and prevent early failure of the material under load.

During a storage period of 45 days at a temperature of +23…+25ºC, the changes in shear stress for all material samples have a wave-like character with a fairly wide spread of cycles of each wave along the length of the material array (Fig. 2). This indicates that the material exhibits variable resistance with increasing external load, where the resistance cyclically increases and decreases.

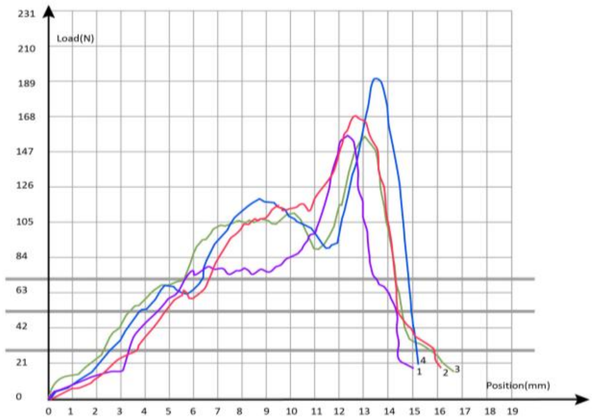

Fig. 2. Structural and mechanical properties of meat snacks without the addition of bee products with a shelf life of 45 days

At the same time, the 2nd cycle of such waves ends at approximately 3/4 of the depth of the samples. This indicates that after passing this depth, the material begins to demonstrate a changed resistance, being subjected to a greater load. These cycles occur with an increase in the amplitude values of the material's resistance. This shows that with each wave the material exerts greater resistance, reaching increasingly greater values of shear stress. The 3rd cycle is marked by change of the shear load of the material mass reaches values of 157 and 189 N, which corresponds to a maximum value of shear strength from 10.46 to 12.79 MPa, i.e. in a rather small interval. Then a characteristic rapid drop in the structural strength of the material is observed. This indicates that all samples reach their peak resistance values at this stage and after reaching a critical load, the material quickly loses its ability to resist external loads.

In snacks with a shelf life of 150 days at a temperature of +18…+25ºC, several clearly defined stages of the process of shearing the sample material were observed during the increase in external force (Fig. 3).

According to the results obtained (Fig. 3), at stage 1 there is a sharp increase in shear stress with the load spreading to a depth of 8…10 mm inside the samples. At stage 2, the shear spreads to a depth of 28 mm with practically no change in internal resistance for sample 1, and for sample 2 there is an increase in shear stress by 50%. At stage 3 the shear load of the material mass reaches values of 107 and 189 N for samples No. 1 and 2, which corresponds to an increase of shear strength to a maximum value of 3.28 MPa for sample 1 and 5.62 MPa for sample 2 over a small shear wavelength of 2 mm; at the same time, the amplitude value of internal resistance for both samples is 30 mm. At stage 4, the internal resistance stabilizes from the sample depth of 33 mm to its end, which can be explained by the formation of a compacted sublayer at the end of the material mass.

The first stage (depth 8–10 mm) of processing was characterized by a sharp increase in shear stress, which indicates the initial reaction of the meat snacks to the applied force and may be associated with overcoming the initial resistance of the material, possibly due to the initial structural adaptation of the material.

During the second stage (depth up to 28 mm), the first sample shows shear propagation without a significant change in internal resistance, which may indicate the homogeneity of the snacks or their ability to plastic deformation. For the second sample, the shear stress increases by 50%, which indicates a difference in the internal structure or composition of the material, which leads to an increase in resistance.

At the third stage (maximum shear stress), there is a sudden increase in shear stress to the maximum value for both samples, indicating the onset of the strength limit of the snacks. The amplitude value of the internal resistance (30 mm) indicates the maximum depth at which the snacks resist shear before catastrophic shear occurs. A significant difference in the maximum shear stresses for the samples (3.28 MPa for the first and 5.62 MPa for the second) indicates different mechanical properties of the meat snacks, in particular, different strength or the presence of a complex structural composition of the product.

The fourth stage (stabilization of internal resistance) is characterized by stabilization of the internal resistance from a depth of 33 mm to the end of the samples, indicating the formation of a compacted sublayer. This may be due to the processes of compaction of the material or reorganization of its internal structure, which ensures constant resistance to the end of the sample.

Different stages of shearing of meat snacks under the influence of external force indicate the presence of different mechanical characteristics of the samples. In particular, a sharp increase in shear stress in the first stage and a jump-like increase in the third stage indicate differences in the structural strength and internal resistance of the product. The first and fourth stages indicate structural changes inside the product under the action of loading, in particular, initial adaptation and formation of a compacted sublayer. A significant difference in shear stresses between the samples (especially in the second and third stages) indicates significant differences in the internal properties and structure of the samples.

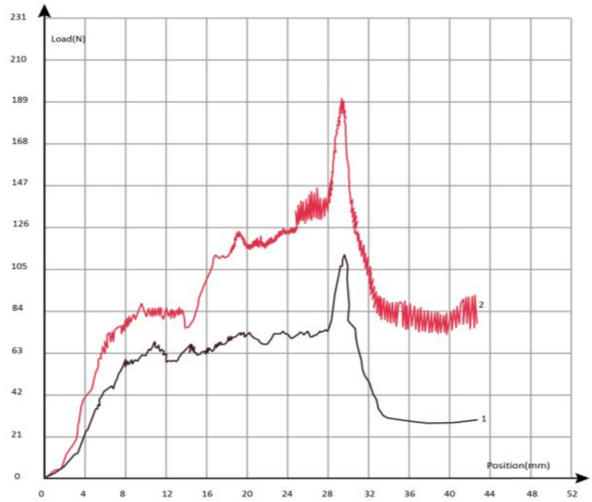

Fig. 3. Structural and mechanical properties of meat snacks without the addition of bee products with a shelf life of 150 days

Structural and mechanical properties of meat snacks with the addition of beekeeping products. In meat snacks with the addition of beekeeping products (honey, aqueous extract of propolis and bee pollen) with a storage period of 1 day at a temperature of +23…+25ºC, a difference was found in the length of the second section of the shear zone, which corresponds to the depth interval of the sample array of 10…36 mm (Fig. 4). At the same time, the shear stress in this section is not completely constant: it slowly increases by approximately 20% from the first jump in the external load. For the resonant section, it can be noted that there is no significant spread in the amplitude values of the shear stresses for different material samples: from 1.28 to 1.93 MPa. The extended length of the second section (from 10 to 36 mm) with a slow increase in shear stress by 20% indicates a more gradual and uniform adaptation of the material to the load. This indicates that the material is gradually subjected to shear without abrupt changes in internal resistance. Such a characteristic may be a sign of greater homogeneity or better structural integrity of the material in this depth interval.

The absence of a significant spread in the amplitude values of shear stresses (from 1.28 to 1.93 MPa) indicates the stability of the material under resonant loading. This may indicate that the material of meat snacks with bee products demonstrates consistent properties, which is important for the expected mechanical behavior. These data emphasize the importance of quality control and formulation selection during the manufacture of meat snacks with the addition of bee products to ensure their structural integrity and stability under mechanical loading.

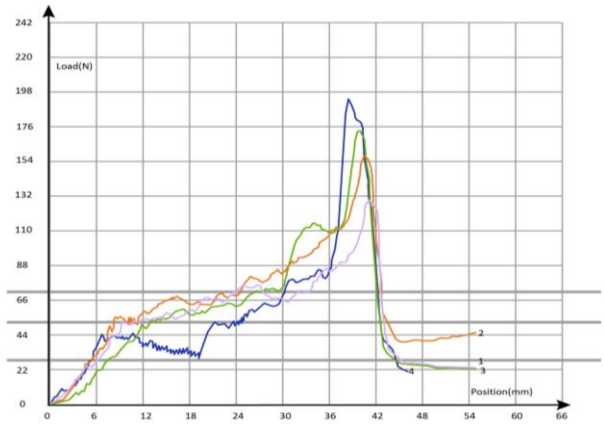

Fig. 4. Structural and mechanical properties of meat snacks with the addition of bee products with a shelf life of 1 day

Fig. 5 shows the dynamics of changes in the structural and mechanical characteristics of snacks with the addition of beekeeping products with a storage period of 45 days at a temperature of +4…+6ºC. According to the dynamics of the studied process, for all material samples, two characteristic areas of shear wave propagation can be noted: a sufficiently intensive increase in the material resistance almost to 2/3 of the depth of action of the external load; resonant increase in the material resistance and a rapid loss of structural strength; the values of the maximum stresses for different samples are in the range of 5.74...9.58 MPa, which corresponds to the depths of shear wave propagation of a slight run-up of 17...19 mm.

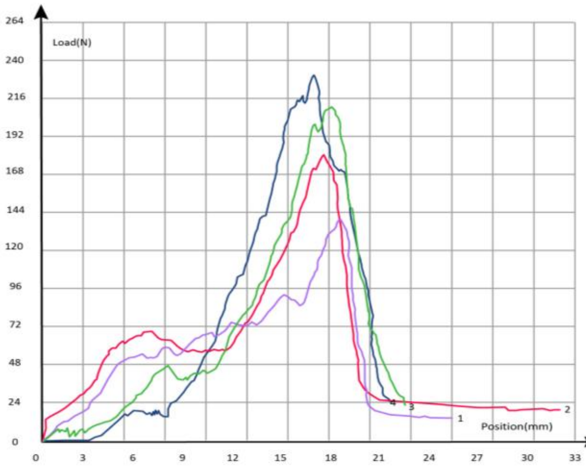

Fig. 5. Structural and mechanical properties of meat snacks with the addition of bee products with a shelf life of 45 days at a temperature of +4…+6℃

The snacks demonstrate high strength up to 2/3 of the loading depth (Fig. 4), which is a positive characteristic for ensuring the stability of the product during initial mechanical stress. A sharp increase in resistance and rapid loss of strength at the final stage indicate a critical strength limit of the material. This means that after reaching a certain level of loading, the material structure cannot withstand further efforts and begins to collapse. A small spread of the depths of shear wave propagation (17–19 mm) indicates the homogeneity and predictability of the mechanical properties of the material among different samples, which is important for ensuring the consistency of product quality.

The results of the study of the characteristics of snacks with the addition of beekeeping products with a storage period of 45 days at a temperature of +25…+28ºC (Fig. 6) differ significantly from those presented above in the following ways: only one cycle of shear stress change in the sample material is observed, that is, only one value of the amplitude increase in the material resistance; the magnitude of the shear stress amplitudes corresponds to a rather insignificant spread of the sample array depths, namely, 38...39 mm, which is approximately 2/3 of the total sample thickness; the stage of decrease in the structural strength of the samples has an extension along the shear wave propagation depth of 9...10 mm, that is, it has the character of an intensive, not a jump-like change; the shape of the shear stress change curve approaches the Gaussian curve, that is, to a normal distribution, which allows us to adequately predict the course of the studied process. Unlike previous studies, only one cycle of shear stress change in the sample material is observed (Fig. 5). This means that the product exhibits a single peak value of the amplitude increase in resistance and does not show repeated cycles of increasing and decreasing voltage, indicating the possibility of accurately determining the moment of maximum strength of the material before its failure.

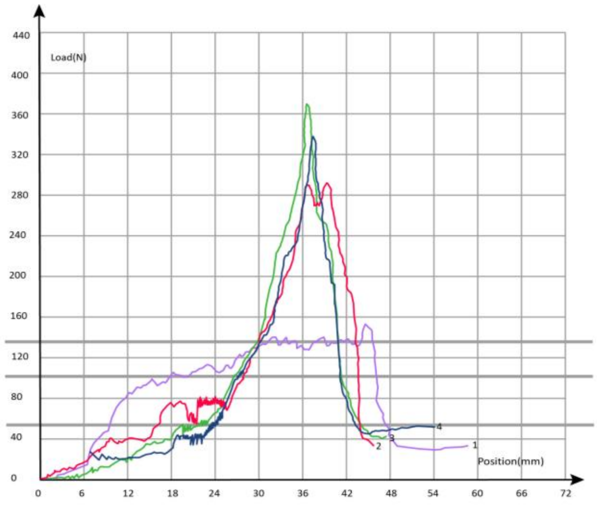

Fig. 6. Structural and mechanical properties of meat snacks with the addition of beekeeping products with a shelf life of 45 days at a temperature of +25…+28ºC.

A slight spread of depths indicates the homogeneity of the material and its stable response to loading within this depth, which is a positive indicator for the production process. An intensive decrease in structural strength can be important for predicting the failure of the material under load, providing a more reliable assessment of its operational characteristics. A curve approaching normal distribution makes it possible to more accurately predict changes in the material under load, which is important for ensuring the quality and safety of the final product. This information can help in optimizing production processes, choosing effective loading conditions and predicting the behavior of meat snacks with the addition of bee products.

For the specified conditions of external force loading of snacks with the addition of beekeeping products with a storage period of 150 days at a temperature of +23…+25ºC (Fig. 6), a wave-like change in shear stress is observed in the material of both samples. The amplitude values of this stress initially increase with a distributed load wave to a depth of 8...10 mm, and then they decrease for load cycles as the shear advances to a depth of 19 mm and 28 mm. These phenomena can be explained by the loss of structural strength of the material with the load advancing already at a third of the depth of the material. The obtained data indicate the complex behavior of meat snacks with the addition of beekeeping products under the influence of external force loading.

Analyzing the obtained data, we observe that the shear stress changes in a wave-like manner in both samples. This may indicate that the material reacts to the external load not uniformly, but with certain fluctuations, which is typical for materials with an uneven internal structure or inhomogeneous composition.

The increase in the amplitudes of the shear stress during the propagation of the load wave to a depth of 8–10 mm indicates the initial response of the material to the applied load. This may be due to the initial adaptation of the material to the external force, where the material structure begins to deform. The decrease in the amplitudes of the shear stress during further advancement of the load to a depth of 19 mm and 28 mm may indicate a loss of structural strength of the material (Fig. 7). This phenomenon indicates that the material is gradually losing its ability to resist shear, probably due to micro-damage or internal structural changes that occur under load. Loss of structural strength of the material as the load advances to one-third of the material depth (approximately 19 mm and 28 mm) may indicate that the material is beginning to collapse or undergo significant deformation, reducing its ability to resist further loading.

The wave-like variation in shear stress and its amplitude may result from the use of bee products, which influence the texture and structural strength of the material. This can be attributed to the presence of biologically active compounds in honey, bee pollen, and propolis – including proteins, lipids, polyphenols, and enzymes – that interact with the protein matrix of the meat product and alter its structural formation. Such modification of the microstructure may lead to an uneven distribution of internal stresses and a reduction in elastic properties under load. These changes are consistent with previous findings, which demonstrated that bee products can affect water-binding capacity, gelation, and overall textural stability in food systems [22]. The observed decrease in shear stress amplitude under continued loading indicates a loss of material strength and elasticity.

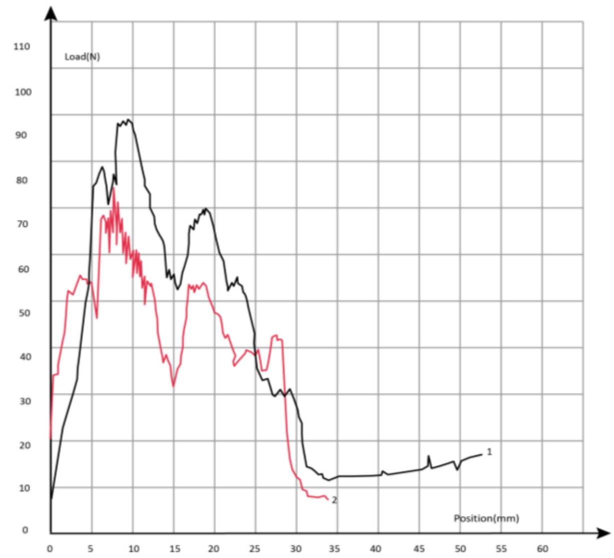

Fig. 7. Structural and mechanical properties of meat snacks with the addition of beekeeping products with a shelf life of 150 days

6. Conclusions

1. The addition of sunflower honey, aqueous propolis extract, and polyfloral bee pollen enhances the structural integrity and resistance of meat snacks during initial mechanical loading, with a maximum stress range of 10.46–12.79 MPa, compared to the control sample (which does not contain bee products).

2. A detailed analysis of each stage of loading on the product base in the form of chicken fillet allowed to indicate the mechanical properties of the samples under the influence of external force and to understand their behavior in the shear

process, which creates prospects for optimizing the formulation and technological processes, which can help improve structural strength and prevent early failure of the material under load.

3. As a result of the conducted research, the optimal ratio of ingredients for the production of meat snacks with the addition of honey, aqueous propolis extract, and bee pollen was experimentally determined. The snacks formulated according to the selected recipe demonstrated the most balanced organoleptic, structural, and functional properties. They contained the highest proportion of chicken fillet (91.35%), which ensured a high protein value, as well as moderate amounts of honey (2%), propolis extract (0.86%), and bee pollen (0.43%), contributing to a pleasant taste without oversaturation.

4. Optimal material adaptation to mechanical load was observed at a shear penetration depth of 10–36 mm, where shear stress increased by 20%, and amplitude values remained within the range of 1.28–1.93 MPa. This indicates high structural homogeneity of the snacks with bee product additives during the initial stage of mechanical impact.

5. After 45 days of storage at 4–6°C, the snacks exhibited maximum shear strength ranging from 5.74 to 9.58 MPa, corresponding to 2/3 of the loading depth (17–19 mm), with a clearly defined critical limit of structural stability. This ensures product integrity during transportation and consumption.

6. Under storage conditions of 150 days at +23…+25°C, the maximum shear force reached 189 N (equivalent to 12.79 MPa); however, the wave-like decrease in amplitude from a depth of 19–28 mm indicates the onset of material structural degradation. This reflects limited long-term structural stability at room temperature.

7. The conducted studies revealed the need to ensure a balance between strength and softness in order to give the product optimal organoleptic properties and preserve its shape and structure during transportation and storage; which is important for assessing their quality, safety, as well as adjusting the production processes of chicken meat snacks to ensure high resistance to mechanical loads under conditions of fluctuations in practical use.

Acknowledgments

The authors Artem Antoniv (#52410255) and Leonora Adamchuk (#52410408) thanks the International Visegrad Fund for scholarships and research internships, during which the results and knowledge presented in this paper were obtain.

References

[1] Bal-Prylypko L. et al.: Comparative data on the content of harmful impurities in honey on the example of ukrainian standards and foreign documents. Journal of Hygienic Engineering and Design 41, 2022, 76–83.
[2] Cakmak H. et al.: Production of crispy bread snacks containing chicken meat and chicken meat powder. Anais da Academia Brasileira de Ciências 88(4), 2016, 2387–2399.
[3] Carrillo Luiset V. et al.: Mathematical Modeling of Goat Meat Drying Kinetics with Thermal Oscillations. Foods 13(23), 2024, 3836 [https://doi.org/10.3390/foods13233836].
[4] Chobot M. et al.: Development of drying and roasting processes for the production of plant-based pro-healthy snacks in the light of nutritional trends and sustainable techniques. Trends in Food Science & Technology 149, 2024, 104553.
[5] Choubey V. et al.: Optimization of Level of Incorporation of Different Dietary Fiber in the Development of Spent Hen Meat Snack Sticks, International Journal of Bio-Resource & Stress Management 15(8), 2024.
[6] Choubey V. et al.: Evaluation of storage stability of dietary fibre incorporated aerobically packaged spent hen meat snacks at ambient temperature. Nutrition & Food Science 54(4), 2024, 677–689 [https://doi.org/10.1108/NFS-10-2023-0230].
[7] Hajam Y. A.: A Review of Its Effects on Gut Microbiota Composition and Functions. Kumar R. (eds): Honey, CRC Press, Boca Raton 2024, 86–108.
[8] Kora A. J.: Applications of sand roasting and baking in the preparation of traditional Indian snacks: nutritional and antioxidant status. Bull Natl Res Cent 43, 2019, 158 [https://doi.org/10.1186/s42269-019-0199-2].
[9] Kumar N., Devi R., Kumar S.: Nutraceutical and Therapeutic Properties of Honeybee Pollen and Its Significance in Honey Industry. Kumar R. (eds): Honey, CRC Press, Boca Raton 2024, 199–210.
[10] Kumar P. et al.: Meat snacks: A novel technological perspective. Innovations in traditional foods 2019, 293–321.
[11] Nimitkeatkai H., Pasada K., Jarerat A.: Incorporation of Tapioca Starch and Wheat Flour on Physicochemical Properties and Sensory Attributes of Meat-Based Snacks from Beef Scraps. Foods 11(7), 2022, 1034 [https://doi.org/10.3390/foods11071034].
[12] Osuna M. B.: Apple Pectin Based Film with Apis Mellifera Honey and/or Propolis Extract as Sources of Active Compounds. Food Biophysics 20(1), 2025, 1–11 [http://dx.doi.org/10.1007/s11483-024-09905-y].
[13] Palamarchuk I., Palamarchuk V., Zheplinska M.: Evaluation of the energy characteristics of the infrared drying process of rapeseed and soybeans with a vibrating wave driver. Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Srodowiska – IAPGOS 14(2), 2024, 42–46 [http://doi.org/10.35784/iapgos.5846].
[14] Prakatur I.: The influence of propolis and bee pollen on chicken meat quality. Veterinarski arhiv 90(6), 2020, 617–625
[15] Sharma D. et al.: Food Processing Potential for Energy Efficiency and Use. Kapoor B. et al. (eds): Environmental Sustainability in the Food Industry. CRC Press, Boca Raton 2022, 79–94.
[16] Sun X. D., Holley R. A.: High hydrostatic pressure effects on the texture of meat and meat products. Journal of Food Science 75(1), 2010, 17–23.
[17] Tornberg E. V. A.: Effects of heat on meat proteins–Implications on structure and quality of meat products. Meat science 70(3), 2025, 493–508.
[18] Younis K. et al.: Incorporation of soluble dietary fiber in comminuted meat products: Special emphasis on changes in textural properties. Bioactive Carbohydrates and Dietary Fibre 27, 2022, 100288.
[19] Zdanowska-Sąsiadek Ż. et al.: Nutrients Composition in Fit Snacks Made from Ostrich, Beef and Chicken Dried Meat. Molecules 23(6), 2018, 1267 [https://doi.org/10.3390/molecules23061267].
[20] Zheplinska M. et al.: Research of Wheat Fiber with Pumpkin Pectin Plant Additive. Ivanov V. et al. (eds): Advances in Design, Simulation and Manufacturing V. DSMIE 2022, Lecture Notes in Mechanical Engineering. Springer, Cham. 2022 [https://doi.org/10.1007/978-3-031-06044-1_23].
[21] Zhu R. et al.: Comparison of four drying methods in terms of the drying efficiency and physicochemical properties of chicken meat. Food Physics 1, 2024, 100010.
[22] Złotek U. et al.: Functional properties of meat products enriched with bee products: Texture, water-holding and antioxidant capacity. Food Chemistry, 321, 2020, 126722 [https://doi.org/10.1016/j.foodchem.2020.126722].

Ph.D. Artem Antoniv
e-mail: artemantoniv@gmail.com

Ph.D. in Food Technology, Independent Research Institute "Ukrainian Science Hub", Brovary, Ukraine.
Research interests: improving the technology of meat snack production using beekeeping products

https://orcid.org/0000-0002-6614-4248

D.Sc. Igor Palamarchuk
e-mail: vibroprocessing@gmail.com

Doctor of Technical Sciences, professor, National University of Life and Environmental Sciences of Ukraine. Department Processes and Equipment of Agricultural Production Processing, Kyiv, Ukraine.
Research interests: design and development of mechanical and heat-mass exchange processes and equipment of processing and food industries with vibromechanical intensification of raw material processing.

http://orcid.org/0000-0002-0441-6586

D.Sc. Leonora Adamchuk
e-mail: leonora.adamchuk@gmail.com

Doctor of Technical Sciences, associate professor, Institute of Veterinary Medicine of the NAAS of Ukraine, Department of Bee Diseases, Kyiv, Ukraine.
Research interests: improving the technology of obtaining and processing beekeeping products based on research into the biodiversity of honey and pollen-bearing plants.

https://orcid.org/0000-0003-2015-7956

Ph.D. Marija Zheplinska
e-mail: jeplinska@ukr.net

Canditate of Technical Sciences, associate professor, National University of Life and Environmental Sciences of Ukraine. Department Processes and Equipment of Agricultural Production Processing, Kyiv, Ukraine.
Research interests: technological and dynamic processes of equipment of food industries.

https://orcid.org/0000-0002-7286-3003