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IMPROVEMENT OF THE MODEL OF STRUCTURAL-MECHANICAL AND THIXOTROPIC PROPERTIES OF MEAT BATTERS

The object of research is the thixotropy of meat batters with different ingredient compositions characteristic of sausage products. The research analyzes modern approaches to evaluating the rheological properties of meat emulsion systems and summarizes the factors influencing their structural organization. The regularities of changes in viscous-plastic characteristics of pork and turkey batters under different levels of load are investigated, and the features of structural destruction and recovery are established.

A comprehensive assessment of thixotropic properties is based on the analysis of the structural-mechanical characteristics of batter systems during their formation with various ingredients. It has been demonstrated that the thixotropic state depends on the concentration of protein components and the degree of hydration of the protein system, which determines the stability of the sausage matrix during mechanical processing. The shear stress was calculated for time intervals in the range of 1–1000 s. The output parameters of the proposed model were adapted to the properties of soft meat batters: for minced pork, coefficients A = 80 Pa and B = –12 were adopted, and for minced turkey, A = 60 Pa and B = –9. Since the value of B is negative for both types of raw materials, this confirms the presence of pronounced thixotropic properties in the studied systems. Controlling these parameters allows regulation of the thixotropy of the batter to achieve optimal consistency and structural stability of the finished product.

Thixotropic properties play a crucial role in technological operations, including grinding, mixing, filling casings, and structure formation during thermal processing. Excessive structural stability complicates processing, while excessive thixotropy reduces the shape retention of products. The determination of rheological parameters allows predicting the behavior of batter systems under production conditions, ensuring stable texture and high product quality. The results obtained have practical value for optimizing technological regimes in sausage production and developing new products with predictable rheological properties.

Keywords: *thixotropy, meat product, sausage products, meat batter, rheological parameters, structural and mechanical properties.*

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1. Introduction

Historically, meat has played a leading role in human nutrition, serving as a primary source of macro- and micronutrients such as proteins, fats, iron, selenium, folic acid, zinc, as well as vitamins A and B12. According to forecasts by the Food and Agriculture Organization of the United Nations (FAO), to meet the growing global demand for food products, meat production volumes are expected to increase by approximately 200 million tons by 2050 [1]. In modern meat production, various types of meat of animal and poultry origin are often combined. The formulations of meat batters include beef, pork, chicken, turkey, lamb, or horse meat in different proportions, which makes it possible to create combined meat systems with a balanced chemical composition and diverse nutritional value [2]. There is a wide range of semi-finished meat products, most of which are made from pork. Such products typically contain a significant amount of intramuscular fat and lard, making them less desirable for consumers who follow healthy eating principles or suffer from digestive and cardiovascular diseases, particularly atherosclerosis. One of the directions for improving the product range is the development of semi-finished products based on poultry meat, which are characterized by moderate caloric content and a high content of macro- and microelements. Effective ways to improve meat batter formulations are based on the use of turkey meat, which is characterized by favorable functional properties, as well as the use of by-products from its processing.

In recent years, the possibilities of modifying the formulation composition of food products have been actively studied. Thanks to modern technological facilities and various methods of recipe modification, it has become possible to purposefully influence the nutritional profile, creating high-quality products that are convenient to prepare, economically feasible, safe, and suitable for industrial production [3]. The perception of products as "healthy" significantly influences the eating behavior of consumers who consciously control their diet to regulate appetite or body weight [4]. The consumption of products perceived as high-fat or low-fat has different effects on their subsequent nutritional value. That is why, in recent years, both scientists and producers have paid special attention to the development of meat products with reduced fat content. However, reducing the fat content to 10% or less often leads to a deterioration in sensory properties – such products become tougher, less juicy and flavorful, darker in color, more expensive, and less appealing to consumers compared to traditional products [5].

There are a growing number of scientific studies devoted to plant proteins as potential meat substitutes that mimic the structure and flavor characteristics of meat. The formation of protein structures of various plant proteins during emulsification for the production of solid fat substitutes has been investigated [6]. Plant-based meat alternatives have been widely studied, ranging from individual products to commonly consumed foods [7]. In addition, research has addressed plant-based alternatives to meat with a focus on driving forces, historical development, production technologies, and consumer attitudes [8].

Scientific interest arises in the rheological and structural characteristics of meat raw materials and the resulting minced beef, due to the need to improve technological processes in the industry [9]. High-pressure processing of beef, usually rejected trimmings for further processing, was considered [10]. The microbiological contamination of fresh meat and the quality of minced meat were investigated [11, 12]. The influence of processing stages on the structural, functional and qualitative properties of beef has been studied [13, 14].

Meat batters continue to occupy a leading position among meat industry products, both in the food service sector and in retail trade. Its popularity is due to its ease of use, stable quality, and wide range of culinary applications. At the same time, meat batter is one of the most perishable products, as the grinding process leads to the destruction of the meat's cellular structure [15]. In turn, this leads to increased losses during thermal treatment due to protein denaturation [16]. At temperatures above 55°C, connective tissue proteins undergo contraction, which causes a more intense release of water, fat, and gelatin, since the water-holding capacity directly depends on the strength of the gel structure [17]. In addition, meat processing technology is considered, taking into account histological identification and evaluation of meat and meat products [18]. Gel formation in minced meat is shown [19]. The measurement of water-holding capacity and juiciness, which is important for studying and analyzing their thixotropic properties, is considered [20].

The process of converting muscle tissue into meat batter requires significant energy input caused by the mechanical grinding of muscle fibers, as a result of which part of the proteins passes into the solution [21, 22]. The technology of meat batter production involves several consecutive stages: preliminary grinding of meat pieces, mixing, main grinding, and forming into trays. The combination of these operations gradually increases the mechanical impact on the product, causing the destruction of cellular structures. Mechanical methods cumulatively increase the amount of non-intact cells (ANIC) [18, 23].

Meat exhibits the properties of a viscoelastic material, capable of partially accumulating the applied force [21]. During technological processing, it is subjected to various types of mechanical load – compression, friction, shear forces, and pressure. In particular, friction arises during mixing and grinding, while pressure occurs when pushing meat through the perforated discs of a meat grinder, increasing as the diameter of the holes decreases. Shear forces arise during the transportation of the product by screw mechanisms and under the action of cutting blades [24]. Grinding is the most common method for reducing the size of meat particles.

Initially, the meat is ground to particles measuring 13–19 mm to ensure uniform mixing with fat, after which it is reground to approximately 3 mm. The degree of muscle fiber disruption depends on the characteristics of the raw material, equipment parameters, and the intensity of the applied force. Therefore, the main factor in the disintegration of muscle structure is mechanical processing – mixing or forming under pressure [17].

As a result of these processes, muscle fibers are destructured, leading to changes in both the structural and mechanical characteristics of the meat. The exposure of the internal cellular structure promotes better protein extraction and increases the amount of soluble fractions. According to German regulations on meat products, ground meat products are allowed to contain a maximum of 20% non-intact cells (ANIC), as determined by histometric methods [17]. An increase in this parameter may lead to an excessively soft, pasty consistency [18].

In addition to histological analysis, other methods are widely used to assess the degree of muscle structure disruption, including the determination of water- and salt-soluble proteins, as well as electron microscopy. At the same time, the water-holding capacity indicates the meat's potential to retain added moisture, while the results of mechanical and sensory texture tests enable the assessment of the firmness and hardness of the final product [20]. Thus, the quality of meat and its perception by consumers directly depend on the degree of structural changes in the cells caused by technological processing.

Therefore, *the object of research* is the thixotropy of meat batters with different ingredient compositions, characteristic of various types of sausage products.

The aim of this research is to develop a model of thixotropic behavior of meat batters based on the relationship between structural and mechanical characteristics and pseudoplasticity under shear loads.

Achieving this aim requires solving the following interrelated *objectives*:

– to investigate the thixotropic properties of meat batters;
– to study the structural and mechanical properties of thixotropy in meat batters;
– to model the thixotropic behavior of meat products using the Weltman model.

2. Materials and Methods

The research employs a comprehensive methodological approach that integrates theoretical, analytical, and empirical tools to study trends in the meat processing industry worldwide. The methodological basis of research includes abstract-logical, comparative, systematic and analytical methods, which, when combined, made it possible to reveal the peculiarities of the application of thixotropy as a criterion for assessing the rheological properties and quality of sausage batters.

The abstract-logical method was used for theoretical generalization of scientific approaches to the research of the structure and properties of meat batter, as well as for formulating the conceptual principles for assessing its thixotropic characteristics. The comparative analysis was used to identify common and distinct features in technological solutions applied in global and domestic practices of sausage production. A systematic approach enabled a comprehensive examination of the processes involved in the formation of meat batter structure, resulting from the interaction of raw materials, technological parameters, and the product's thixotropic properties.

The step test (three-interval thixotropy test, 3ITT) is usually performed using a rotational rheometer with rapid speed changes. The step test consists of three intervals and is therefore called the "3-interval thixotropy test" (3ITT). It can be performed either in controlled shear rate (CSR) mode or in controlled shear stress (CSS) mode: in CSR mode, the shear rate or rotation speed is predetermined, while in CSS mode, the shear stress or torque is predetermined on the viscometer. The test is performed at two different speeds/shear rates. The first and last intervals are performed at low shear rate, and the second interval at high shear rate.

For the quantitative evaluation of the thixotropic properties of meat batters, rheological methods are used, based on measuring changes in viscosity or shear stress during repeated loading and unloading of the sample. The most common devices are rotational viscometers (such as Rheotest Medingen GmbH RN 4.1, Germany, and Brookfield RST CPS, AMETEK Brookfield, USA) and rheometers with controlled shear rate.

The informational basis of the research comprises scientific publications, regulatory and technical documentation, and periodical editions focused on the development of meat-processing technologies, the improvement of sausage batter formulations, and the enhancement of the quality of finished products. The use of these sources provided an opportunity to systematize, critically analyze and generalize scientific approaches, as well as to formulate independent conclusions regarding ways to improve the efficiency of sausage production based on the research of the thixotropic properties of meat batter.

3. Results and Discussion

3.1. Investigation of the thixotropic properties of meat batters

Thixotropy is the property of certain substances and gels, including sausage batters, to become less viscous when a constant force is applied, and to fully restore their original viscosity over time once the force is removed. The higher the force applied, the lower the viscosity becomes. Thixotropy is a time-dependent phenomenon, as the viscosity of a substance must recover after a certain period of time when the applied force is removed.

The term thixotropy comes from the Greek words thixis ("to touch") and trepein ("to turn"). It denotes the reversible change or transition in the structure of a substance when subjected to mechanical stress. For example, sausage minces flows out of the nozzle of a syringe when it is squeezed. Its viscosity decreases when force is applied. Once the force is removed, the viscosity returns to its original state. This means that thixotropic behavior is always combined with shear flow behavior. In general, there are three different types of time-dependent flow behavior.

Time-dependent viscosity changes during the 3ITT test reflect the actual behavior of the sample before, during and after pressure removal (Fig. 1).

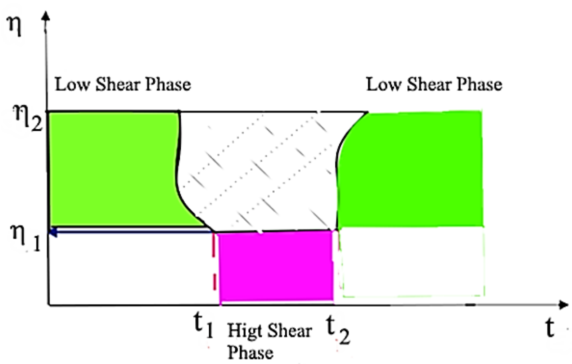

Fig. 1. Dependence of sample viscosity on time with thixotropic behavior: η – viscosity, t – time

1. Low shear phase: The purpose of the first interval is to achieve a constant viscosity at a constant low shear rate. This interval provides the reference viscosity of the sample at rest.
2. High shear phase: In this interval, the sample is sheared at a constant high shear rate to simulate the behavior of the sample during mince filling, for example, when pumping mince through a syringe. The structural pressure distribution can be determined by the behavior of the sample during creep and shear, also known as pseudoplastic behavior.
3. Low shear phase: Here, the same constant low shear rate is defined as in the first interval. This interval allows the sample to recover its structure/viscosity.

For the initial assessment of meat products, it is essential to understand their structure, specifically the nature of the spatial relationship between particles. A continuous spatial framework is formed as a result of contact between dispersed particles or macromolecules, between which forces of interaction of various natures arise. The spatial structure of the framework depends on the type of energy that causes these bonds and is divided into several types of structures according to the 4K principle (Fig. 2).

Coagulation structures are formed as a result of the adhesion of particles through thin layers of the dispersion medium (free or adsorption-bound), which is caused by the action of Van der Waals forces. They are characterized by thixotropic properties – the ability to reduce viscosity under mechanical stress and to restore the original structure after the cessation of this stress. Thixotropy is the result of a dynamic equilibrium between the breakdown and restoration of structural bonds within the system. During deformation (mixing, grinding, mincing), weak interparticle contacts are disrupted, leading to a thinning of the system; after the cessation of shear, these bonds gradually recover.

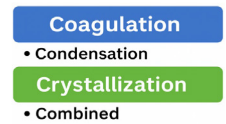

Fig. 2. Framework structures of meat batter depending on the type of energy according to the 4K principle

In highly concentrated coagulation-type systems, compaction and increased structural strength are observed, while in weakly concentrated systems, syneresis occurs with partial strengthening due to the displacement of part of the liquid. Free liquid can be released as a separate phase or remain in the structure in the form of small droplets. The strength of coagulation structures increases gradually to a certain limit, after which it stabilizes.

Condensation structures are formed from coagulation structures during the removal of the liquid phase, which leads to the formation of closer interparticle contacts. As a result, the structural strength increases and becomes constant. Such structures are stronger than coagulation ones; however, they are not capable of self-recovery after destruction and are characterized by brittleness and low plasticity.

Crystallization structures arise as a result of the intergrowth of particles or molecules involving chemical interactions, occurring during the cooling of melts or the concentration of solutions. They are characterized by the presence of spatial crystal lattices, the strength of which depends on the shape and size of the crystals. Initially, a thermodynamically unstable, less strong modification is usually formed, which over time transforms into a stable, stronger form.

Most meat products are characterized by a coagulation-type structure caused by the interaction between particles of the dispersed phase through a liquid medium. Structures of this type are characterized by thixotropy, i. e. the ability to temporarily liquefy under mechanical stress and recover after the deformation ceases. Thixotropic properties are extremely important in meat processing technology, as they provide optimal conditions for grinding, mixing, forming, filling casings and structure formation during thermal processing. Excessive structural stability can complicate technological operations, while excessive thixotropy leads to a decrease in the dimensional stability of products.

The structural and mechanical properties of coagulation systems depend significantly on moisture content, particle size, the thickness of interparticle layers, as well as their physicochemical characteristics. Regulation of these parameters makes it possible to purposefully influence the thixotropic behavior of meat batters and achieve the desired consistency of the finished product.

A typical example of a product with a coagulation structure is raw sausage batter. In this system, the discontinuous (dispersed) phase is represented by protein particles and aggregates, fat inclusions, as well as small fragments of muscle and fat tissue.

The continuous phase is an aqueous solution of soluble proteins, organic compounds and electrolytes (mainly sodium chloride). The proteins that pass into the continuous phase give the meat batter its plasticity, stickiness, ability to bind moisture and thixotropic recovery after mechanical action, which significantly affects the formation of the structure and consistency of the finished product.

3.2. Study of the structural and mechanical properties of thixotropy in meat batters

For the quantitative determination of the structural-mechanical properties of thixotropic meat batters, rheological methods are used. These methods are based on measuring changes in viscosity or shear stress during repeated loading and unloading of the sample. Thixotropy is determined by the area of the hysteresis loop on the "shear rate – shear stress" curves, which characterizes the degree of structural destruction and the rate of recovery. In addition, meat technology practices use penetration tests, elastic recovery measurements, and stress relaxation time to assess the structural stability and plasticity of systems after mechanical impact.

Condensation structures include batters used to produce cooked and dry-smoked sausages. The formation of a solid monolithic structure of cooked sausages is caused by the emergence and development of a spatial protein framework as a result of thermal denaturation and coagulation of proteins dissolved in the continuous phase of the raw batter. The strong, predominantly hydrogen bonds formed during thermal processing provide the framework with static strength and resistance to shear deformation.

The formation of the structure of dry-smoked sausage batter occurs as a result of the combination of two oppositely directed processes:

– enzymatic degradation of residual cellular structures;
– spontaneous aggregation of protein particles into a spatial framework due to the gradual dehydration of the system.

In this case, in addition to hydrogen bonds, stronger covalent bonds are also formed, which increase the stability of the structure.

The structural and mechanical properties of a product, depending on the type of external forces, characterize its behavior under external loads and allow establishing the relationship between stresses and deformation rates during the application of forces. Depending on the nature of the applied external forces and the deformations caused by them, structural and mechanical properties are divided into three main groups (Fig. 3).

Fig. 3. Groups of structural and mechanical deformation properties

Compression properties determine the behavior of the product when subjected to normal stresses in a closed volume or between plates. The parameters characterizing these properties include: elastic modulus, equilibrium modulus, and relaxation period of deformation under constant stress.

Surface properties (adhesion, external friction coefficient, etc.) occupy a special place among structural and mechanical characteristics. They determine the behavior of the product at the interface with another solid material under the action of normal (adhesion) and tangential (external friction) stresses. The magnitude of surface properties significantly affects the rheological characteristics of the system and the formation of the consistency of the finished product.

Strength indicators (cutting force, compression deformation) and elasticity indicators (elastic deformation, elastic modulus) can be used as objective characteristics of the finished product.

3.3. Modeling the thixotropic and anti-thixotropic behavior of meat products

The thixotropic behavior of meat products was modeled using the Weltman model. This model is widely used to characterize thixotropic and anti-thixotropic products [5]. Its equation is as follows

$$\tau = A - B\log t,$$

where τ – shear stress, Pa; t – time, s; A – stress value at $t = 1$ s; B – the coefficient of structure fluidity over time; the value of B is negative, and for anti-thixotropic structures, it is positive.

The Weltman model is used to describe the thixotropic/anti-thixotropic behavior of food systems (the model uses numerical values (A and B), which are usually given for specific experimental data and are rarely standardized). The most probable/representative values (A and B) were used for modelling.

To perform the calculations, the following shear stress times were assumed:

$$t_1 = 1 \text{ s}, t_2 = 10 \text{ s}, t_3 = 100 \text{ s}, t_4 = 1000 \text{ s}.$$

The selected parameters for the calculations are comparable to the typical values for soft meat batters:

– pork batter: $A = 80$ Pa; $B = -12$ ($B < 0 \Rightarrow$ thixotropy);
– turkey batter: $A = 60$ Pa; $B = -9$ ($B < 0 \Rightarrow$ thixotropy).

The values of B depend on the viscosity of the batter, its composition, moisture content, fat content, temperature and shear rate. To assess thixotropy, it is recommended to determine parameter B experimentally for each batter under study using the methods described above. The value of B depends on the actual behavior of the batter in terms of protein composition, protein content of plant ingredients, taking into account fat content, temperature, prior processing, etc.

Since $B < 0$ (Fig. 4), this means that under prolonged shear the stress increases in the manner indicated (for other data sets, the sign of B may be different).

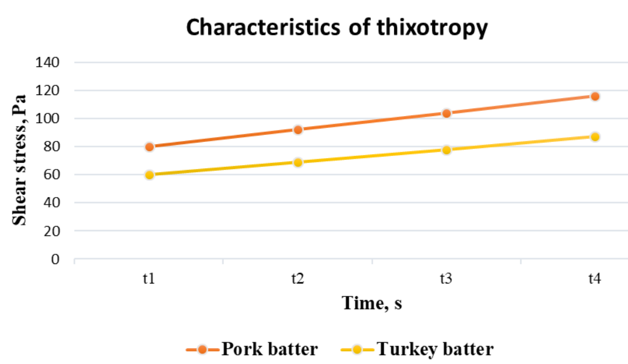

Fig. 4. Graph of thixotropy changes in pork and turkey batters

The thixotropic parameters of turkey batter indicate that it contains less fat and, at the same time, has higher protein content than pork, which makes it a promising raw material for the development of healthier meat semi-finished products [25, 26].

The chemical composition of turkey meat is characterized by a protein content of about 25% and a fat content of approximately 4%. For comparison, the protein complex of broiler chicken meat contains up to 92% of the essential amino acids required by the human body. The lipid content of chicken meat is approximately 11%, with a significant proportion represented by unsaturated fatty acids. This composition determines their low melting point and favorable dietary properties, making poultry meat a valuable component to produce functional meat products.

The research of the thixotropic properties of meat systems is extremely important and promising for further scientific research and practical developments in the field of meat processing.

Scientists have described the rheological properties of meat batter, in particular structural viscosity, plasticity, and, under certain conditions, thixotropy [27]. In particular, studies on the main factors affecting the flow properties of homogenates of beef muscles and meat emulsions relevant to sausage production have been reviewed [28]. The apparent viscosity and yield value were measured using a coaxial cylindrical viscometer. The homogenates exhibit structural viscosity, plasticity, and, under certain conditions, a degree of thixotropy. The rheological behavior of homogenates is influenced by post-mortem time, pH, NaCl, and added water. The amount of added fat and the temperature also affect sausage-type emulsions. The results highlight the following key factors influencing the rheological properties of meat batters and meat emulsions: changes in water-holding capacity and swelling, modifications in myosin-actin interactions, the solubility of myofibrillar proteins, and the physical state of fat.

To determine the average proportion of lean and fatty meat, fat content was measured in samples of beef and beef-pork batters [29]. A total of 98 meat samples were analyzed, of which 59% of the beef batter samples and 20% of the beef-pork batter samples contained less than 10% fat by weight. On average, beef batter contained approximately 9.4% fat by weight, whereas beef-pork batter contained about 15% fat by weight. The lowest measured fat concentration was 1.9%, and the highest was 24% by weight.

Changes in the rheological behavior, thermal and structural properties of the meat batter were also examined through the addition of κ-carrageenan [30]. The aim of this research was to investigate the effect of adding κ-carrageenan (KC) at different levels (0.1, 0.2, 0.3, and 0.4% w/w) on the rheological behavior, thermal properties and microstructure of myofibrillar protein (MP) gels, as mediated by NaCl concentration (0.3 and 0.6 M). The rheological behavior indicated that the incorporation of KC enhances the interaction between KC and MP, resulting in a denser and more compact intermolecular gel-like network structure of the sample. Moreover, the presence of KC increases the enthalpy of the mixed MP-KC gels and promotes the formation of larger aggregates, primarily due to hydrophobic interactions and hydrogen bonding between MP and KC. Moreover, a NaCl concentration of 0.6 M provided relatively higher rheological properties, enthalpy values, and α-helix content, as well as smaller aggregates in the mixed MP-KC gels ($P < 0.05$), compared to those with a lower NaCl concentration (0.3 M). These results provided a deep understanding of the interactions between MP and KC, facilitating the development and design of MP-KC-based products with desired properties.

Furthermore, the functional potential of using two types of plant oil emulsions (from chia and grape seed) as substitutes for animal fat in the formulation of cooked sausages was also investigated [31]. To evaluate the effect of different levels of fat replacement with chia and grape seed oil emulsions on structural changes and the stability of sausage emulsions, scanning electron microscopy (SEM) and texture profile analysis (TPA) were used [32]. A direct correlation was observed between TPA-measured hardness and the addition of chia oil emulsion. A decrease in adhesiveness was observed in the test samples compared to the control ($P > 0.05$) when fat was fully or partially replaced with grape seed oil emulsion. Conversely, adhesiveness increased in the samples containing chia oil emulsion, with the increase being directly proportional to its concentration.

The microstructure of sausage samples was analyzed using scanning electron microscopy (SEM). It has been established that partial replacement of pork fat with emulsified chia and grape seed oils contributes to the formation of a more compact product matrix. These samples were characterized by smaller fat droplets compared to the control and the sample containing only grape seed oil.

In summary, the use of chia and grape seed oil emulsions was recognized as a viable alternative for replacing animal fat in emulsified meat sausages. The addition of pre-emulsified chia oil resulted in products that were similar to the standard in terms of texture, microstructural characteristics, and emulsion stability, while also improving the nutritional profile and healthfulness of the final product.

Beef sausages enriched with common bean flour were produced using five levels of fat content and added water (AW): 25% fat/5% AW; 20% fat/10% AW; 15% fat/15% AW; 10% fat/20% AW and 5% fat/25% AW [33]. Reducing the fat content while increasing the amount of added water had no effect ($P > 0.05$) on pH and ash content, but reduced the yield of the product during cooking and increased the apparent moisture content. The lowest L^* (lightness) values ($P < 0.05$) were recorded for the formulation containing 25% fat and 5% added water (AW). A meat batter with a high fat content and low water content required greater shear stress during extrusion than a meat batter with a low-fat content and high-water content. The textural characteristics of beef sausage were reduced by replacing added water with fat.

Thus, the rheological characteristics of meat batter (structural viscosity, plasticity, and thixotropy) determine the quality, stability, and processability of meat emulsions and finished sausage products. Studies show that these properties are significantly influenced by fat content, the amount of added water, salt concentration, pH, post-mortem time, as well as the use of functional additives (including κ-carrageenan, protein concentrates, or plant-based emulsions [34]).

In particular, replacing animal fat with plant oil emulsions (chia and grape seed) and using κ-carrageenan leads to changes in the structure and rheological behavior of meat systems, forming a more compact and stable gel matrix.

Thus, the research of thixotropy as a dynamic rheological characteristic is essential for understanding structure formation processes in meat emulsions, optimizing formulations, and improving technologies for the production of sausage products with enhanced textural and functional properties.

3.4. Limitations and directions of research development

The application of the proposed approaches for determining the thixotropic properties of meat batters will allow for accounting of their stability in products when various experimental data are available. Furthermore, it will enable consideration of the characteristics of batter formation with different additives, fillers, fat and muscle content, the presence of plant-based proteins, and so on.

Practical significance of the research results:

– the developed approaches to assessing thixotropy allow for the improvement of meat grinding, mixing, and forming processes, ensuring the rational use of energy resources and equipment;

– the proposed model of thixotropic behavior is the basis for developing recommendations that increase the stability of emulsion systems and prevent the formation of defects (e. g., broth-fat swelling) in sausage production;

– the data obtained provide a scientific basis for the implementation of automated real-time monitoring systems for the rheological characteristics of meat batter at key stages of production.

Research limitations. The application of the Weltman model to describe the thixotropic and anti-thixotropic behavior of food systems involves the use of parameters A and B, which numerical values are usually determined for specific experimental conditions and are not uniformly standardized. Within the scope of this research, the most probable and representative values of parameters A and B were used to model changes in the thixotropic properties of pork and turkey meat batters, justified on the basis of an analysis of the literature and previous experimental data.

At the same time, it should be noted that parameter B, which characterizes the intensity of thixotropic changes, should be determined experimentally for each type of meat batter using appropriate rheological methods. This is due to its dependence on the actual rheological behavior of the system, in particular the protein composition, the presence of plant protein ingredients, the fat content, temperature conditions, and the nature of the previous technological processing.

The main limitation of this research is the lack of specialized rheological equipment (viscometers), which made it impossible to experimentally determine the individual values of the Weltman model parameters for each of the meat batters investigated. In this regard, the obtained results should be considered within the adopted assumptions and used primarily for comparative analysis and qualitative assessment of the thixotropic behavior of the systems under study.

Prospects for further research. Further research will focus on evaluating the physicochemical properties of plant-based meat analogues based on soy, pea proteins, etc. The data obtained will enable the development of structured analogues (biomimetic products) of products with a reproduced fibrous structure of muscle tissue using the method of controlled protein texturization.

4. Conclusions

1. The rheological parameters (yield stress and dynamic viscosity) describing the ability of meat batters to recover after shear deformation has been determined. It has been found that the investigated systems exhibit a pseudoplastic flow behavior, which is characterized by the energy of destruction of structural bonds.

2. The change in the viscosity of meat products under increasing shear stress was modeled. The model allows predicting the behavior of the meat batter at different stages of the technological process (grinding, stuffing) and optimizing the formulation to ensure the desired consistency of the finished product.

3. It has been proven that the thixotropic state of meat batters depends on the concentration of protein components and the degree of hydration of the protein system, which directly affects the stability of the sausage matrix during mechanical processing. The shear stress was calculated for time intervals t in the range of 1 – 1000 s. The output parameters of the proposed model were adapted to the properties of soft meat batters: for minced pork, coefficients $A = 80$ Pa and $B = -12$ were adopted, and for minced turkey, $A = 60$ Pa and $B = -9$. Since the value of B is negative ($B < 0$) for both types of raw materials, this confirms the presence of pronounced thixotropic properties in the studied systems.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, including financial, personal, authorship, or any other, that could affect the research, and its results presented in this article.

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The research was performed without financial support.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating this work.

Authors' contributions

Ihor Oshchypok: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review and editing; ***Halyna Kushniruk:*** Conceptualization, Formal analysis, Writing – original draft, Writing – review and editing, Supervision; ***Olia Masliichuk:*** Methodology, Investigation, Writing – review and editing; ***Olga Vivcharuk:*** Methodology, Formal analysis, Writing – original draft, Writing – review and editing; ***Oksana Pauk:*** Investigation, Visualization, Writing – review and editing.

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