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SUBSTANTIATING THE EFFICIENCY OF USING PACKAGING WITH OXYGEN ABSORBER WHEN STORING SMALL-PIECE NATURAL SEMI-FINISHED MEAT PRODUCTS

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This study's object is the process of storing small-piece natural meat semi-finished products in packaging with an oxygen sorbent. The task addressed relates to determining the safe shelf life of the product without deterioration in quality indicators.

The application of packaging with an oxygen sorbent could significantly prolong the shelf life of semi-finished products before their use. The dynamics of changes in the physicochemical, functional, and organoleptic indicators of the product during storage have been studied. The samples were packaged in barrier polymer packaging in two variants: control (without absorber) and experimental (with oxygen absorber). Storage was carried out at a temperature of minus 1…1°C for 14 days. The change in pH, water-holding capacity, transformation of the content of essential macronutrients and sensory characteristics was studied. It was found that beef retains moisture better than pork due to its lower fat content. In pork, on the contrary, high fat content leads to significant moisture loss, especially under normal storage conditions after 5–7 days.

The use of an oxygen sorbent helps maintain a high moisture-holding capacity of meat for up to 14 days. It was shown that samples with sorbent demonstrated more stable, linear moisture retention, while control samples lost it much faster. Studies have shown a strong feedback between pH level and water-holding capacity, which makes it possible to predict changes in the latter.

During the storage of meat semi-finished products without oxygen sorbent, a more intense decrease in protein was observed, a relative increase in fat due to dehydration with an increased risk of oxidation and accumulation of carbohydrates, while the use of sorbent helped restrain these negative changes. Thus, the use of oxygen absorbers in the composition of active packaging contributes to the preservation of physicochemical and sensory indicators of meat semi-finished products, reduces the intensity of oxidative processes, and extends their shelf life by 5–6 days without the use of preservatives.

The results could be used for designing innovative packaging for chilled meat products

Keywords: semi-finished meat products, shelf life, oxygen sorbent, active packaging, macronutrient content, sensory properties

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1. Introduction

Under the current conditions of food industry development, there is a growing demand for products that combine ease of use, high quality, and safety, as well as have a long shelf life without the use of chemical preservatives. One of the most popular categories in the consumer market is natural small-piece meat semi-finished products, which are characterized by the speed of preparation and preservation of the taste qualities of meat raw materials. However, given the high moisture content, significant protein content, and large area of contact with air, these products have a limited shelf life and are prone to spoilage and oxidative processes.

One of the promising areas of food technology is the use of modern packaging with oxygen absorbers, which reduce the level of oxygen in the internal environment of the package, thereby limiting the development of oxidative reactions and the growth of aerobic microorganisms. This approach has already demonstrated its effectiveness in the storage of some types of meat products.

Based on the above, one can note that research on studying the quality indicators and extending the shelf life of small-piece natural meat semi-finished products stored in packaging with an oxygen absorber is relevant.

2. Literature review and problem statement

In [1] it is stated that the requirements for packaging and products intended for contact with food products are systematically increasing. This is due to the enhanced interest of consumers in fresh products with a long shelf life and controlled quality. In response to this challenge, the food industry and packaging manufacturers are actively developing new and improved concepts of packaging technology, seeking to improve such properties of materials as gas barrier, protection against ultraviolet radiation, extension of shelf life, transparency, and environmental friendliness. Despite the active development of technologies for active and intelligent packaging of food products, the problem of the lack of a clear and harmonized regulatory framework that would fully take into account the specificity of such packaging systems remains unresolved.

Preservation of the quality of packaged food products [2], in particular by preventing their oxidation, is a key factor for increasing the shelf life, ensuring attractiveness, and improving safety. However, the problem of insufficient awareness and consumer trust in such innovative packaging solutions remains unresolved. Limited understanding of the mechanisms of action of active packaging, its safety and benefits by end users hinders the widespread implementation of such technologies in the food market. This situation requires the development of effective communication strategies and educational activities aimed at increasing awareness and strengthening consumer trust in innovative packaging systems.

The authors of work [3] investigate the effectiveness of oxygen absorbers for extending the shelf life of cooked meat products stored under light in a modified atmosphere, using packaging materials with high and low oxygen permeability. The results of their studies confirm that an important role in this belongs to oxygen absorbers, which effectively remove dissolved oxygen, maintaining the color, consistency, and odor of products, and most importantly – preventing the growth of microorganisms that cause spoilage. Despite the proven effectiveness of oxygen absorbers in preserving the quality of cooked meat products during storage under light conditions, the problem of the lack of comprehensive and generalized recommendations for combining the type of absorber, the characteristics of the packaging material, and storage conditions remains unresolved. The results of the experiments indicate a strong dependence of the efficiency of absorbers on the interaction of the above-mentioned factors, which requires further research.

Ferric oxides have been shown to be the most reliable and widely used oxygen scavengers, making research in this area promising. Initially, oxygen scavengers were in the form of bags of iron powder, but they have now evolved into self-adhesive patches of any size, capacity, and purpose, effectively reducing oxygen concentrations to 100 ppm in a variety of foods and beverages [4]. Despite the recognized effectiveness of oxygen scavengers in preserving food quality, the problem of determining the long-term impact of these systems on the physicochemical, organoleptic, and microbiological characteristics of various groups of products remains unresolved. In addition, there is limited data on possible undesirable interactions between the components of the scavengers and the food environment.

Oxygen scavengers are used in the form of films, sachets, powders, or as an integrated part of the packaging material [5]. However, the issues related to barrier polymer packaging intended for the storage of natural meat cutlets have remained unresolved.

In work [6], organic and inorganic oxygen scavengers, such as iron and ascorbic acid, were reviewed in detail, and the mechanism of action of light-activated systems, renewable organic compounds, and unsaturated hydrocarbon-based scavengers was explained. However, the authors did not investigate the packaging with an oxygen scavenger for the storage of meat products. Similarly, study [7] focused on the use, characteristics, and application of oxygen scavengers in food packaging but the object was not meat cutlets.

The authors of [8] confirmed the relevance of using oxygen absorbers in a packaged product by demonstrating the extension of the shelf life of sliced bread up to 12 days using active packaging with oxygen absorbers and a modified atmosphere. Although the use of oxygen absorber systems demonstrates high efficiency in extending the shelf life of sliced bread, the problem of the lack of adapted and optimized strategies for using such systems, taking into account the specificity of individual bakery products and their storage conditions, remains unresolved. The lack of comprehensive data on the relationship between the type of bread, packaging material parameters, active components, and operating conditions limits the implementation of universally effective solutions for active packaging in this category of food products.

At the same time, although paper [9] considers the use of unpleasant taste absorbers in active packaging to combat undesirable flavors in food products, the specificity of their application specifically for meat products have not been sufficiently highlighted.

The quality and shelf life of meat products are determined by their color, odor, texture, and taste, which depend on many internal and external factors. The authors of [10] consider the use of food preservatives and additives in the meat industry to extend shelf life, prevent microbiological spoilage, and maintain quality. Methods for detecting these substances in meat products are also described. Issues of safety, regulation, consumer perception, and analytical technologies are raised. However, the problem of the lack of rapid, affordable, accurate, and standardized methods for detecting food preservatives and additives in meat products that simultaneously meet the requirements of quality control and safety remains unresolved.

The authors of [11] analyze existing solutions: vacuum packaging, modified atmosphere, active and intelligent packaging, biodegradable materials. Existing technologies, as a rule, solve only individual tasks – for example, reduce spoilage but can be difficult to dispose of or expensive. However, despite significant progress in the development of meat packaging technologies, the problem of the lack of a comprehensive, universal packaging solution that would simultaneously ensure quality, safety, extended shelf life, environmental sustainability, and cost-effectiveness remains unresolved.

Despite the growing interest in natural antioxidants to improve the oxidative stability of meat, the authors of [12] have not investigated the oxygen sorbent as a separate or integrated element. Although the technology of functional packaging of meat products is constantly evolving to extend shelf life and maintain freshness [13], the authors of work [14] investigate food preservatives as alternative substances for food packaging, rather than oxygen scavengers.

Paper [15] reports the results of studies on the use of oxygen absorbers and active packaging for food preservation. It has been shown that the use of oxygen absorbers significantly improves the quality and shelf life of products, minimizing oxidative processes and the growth of microorganisms. However, issues related to the adaptation and efficiency of active packaging systems containing oxygen absorbers for the storage of meat products, in particular small-piece natural semi-finished products, remain unresolved.

Our review of the literature indicates significant progress in the development of active packaging technologies for food products, in particular with the use of oxygen absorbers. However, a generalization of the scientific data gives grounds to identify a number of unresolved problems that hinder the effective and large-scale implementation of such systems. In general, attention is focused on general aspects of the use of preservatives, antioxidants, and other active components, without a clear focus on meat products as an object of packaging, in particular semi-finished products with a short shelf life. The issue of the effectiveness of packaging technology with an oxygen absorber specifically for small-piece natural meat semi-finished products remains insufficiently researched.

All this gives grounds to argue for the feasibility of conducting a study aimed at investigating the effectiveness of using oxygen absorbers in active packaging to extend the shelf life and preserve the quality of small-piece natural meat semi-finished products.

3. The aim and objectives of the study

The aim of our study is to substantiate the effectiveness of using packaging with an oxygen absorber in the storage of small-piece natural meat semi-finished products by studying the dynamics of changes in the physicochemical, nutritional, and organoleptic parameters of the product during storage. This will make it possible to prolong the shelf life of semi-finished products before their use.

To achieve this aim, the following objectives were accomplished:

– to analyze changes in the pH of small-piece natural meat semi-finished products during storage in packaging with an oxygen absorber compared to the control group without an absorber;

– to assess the effect of an oxygen absorber on the dynamics of changes in the moisture-holding capacity of meat semi-finished products during storage;

– to investigate the transformations of the content of basic macronutrients (proteins, fats, carbohydrates) and the energy value of meat semi-finished products under the influence of storage conditions using an oxygen absorber;

– to establish changes in the organoleptic properties of test samples during storage.

4. The study materials and methods

The object of our study is the process of storing small-piece natural meat semi-finished products in packaging with an oxygen sorbent. This food product is a complex biochemical system characterized by high sensitivity to storage conditions, in particular to oxygen oxidation, microbial spoilage, and loss of sensory properties.

The principal hypothesis of the study assumes the use of an oxygen sorbent in the active packaging system, which makes it possible to maintain the optimal gas composition, thereby reducing the intensity of oxidative changes in the structure of meat semi-finished products. This will make it possible to preserve the physicochemical characteristics, nutritional and energy value, as well as organoleptic properties of semi-finished products throughout the entire storage period.

In order to ensure the reproducibility of the experiment and the validity of the interpretation of the results, assumptions were formulated during the study that outline the boundary conditions and methodological framework of our research:

– it was assumed that all samples of small-piece natural meat semi-finished products are homogeneous in composition, physical-chemical characteristics, and microbiological state at the time of inclusion in the experiment;

– it was assumed that the temperature regime, relative humidity, and light level under storage conditions remain constant throughout the entire experimental period and do not have a variable effect on the quality of the product;

– it was assumed that the packaging material has low gas permeability, and the change in the gas composition inside the package is mainly due to the metabolic activity of the product and the action of the oxygen sorbent;

– it was assumed that the elements of the active packaging, with the exception of the functional effect of the oxygen sorbent, do not react with the components of the meat product and do not change its physical-chemical or organoleptic properties;

– within the framework of our study, the main factor in changing the quality of semi-finished products was considered to be the oxygen content, which causes the development of oxidative processes.

In the process of research, a number of methodological simplifications were also adopted, necessary for the unification of the experimental conditions: the use of one type of oxygen sorbent, the dimensions of the package, the volume of the gas medium, and the mass of the samples were standardized for all experimental series, as well as fixed shelf life, a limited list of analytical indicators.

For packaging natural meat semi-finished products in the studies, sealing trays covered with a special film that makes it possible to weld with polyethylene were used. The trays are manufactured by the company "Accord Plastic" in the city of Kyiv (Ukraine).

Transparent barrier film is used to seal containers. It has a universal welding layer and is widely used in tray packaging using MGS, Skin, Darfresh, and freezing technologies. The film is made of environmentally friendly materials, which guarantees safety of use in food production. Oxygen absorber (sorbent) DX-H-100 – placed in food packages. Oxygen sorbent DX-H-100 comes from the manufacturer in "sachets" with iron powder, which have a size of 40×50 mm. Each sachet contains 3.0 ± 0.2 grams of sorbent. One DX-H-100 sachet is designed for use in packages with products with a total air volume of not more than 1760 ml. The manufacturer's recommendations state that the time interval from the removal of the sachet from the packaging to the moment of placing it in the package with meat semi-finished products should not exceed 60 minutes. After 24 hours, the oxygen level in the package decreases to 0.01%. Subsequently, oxygen that penetrates through the package will be absorbed. The DX-H-100 absorber has a sorption capacity of 360 ml of oxygen. Similar packaging was used as a control, but without an oxygen sorbent.

For the production of natural small-piece meat semi-finished products, chilled beef and pork were supplied in the form of half-carcasses. Previously, the marking mark was removed from the surface of the carcass, residual dirt and blood clots were removed, after which sanitary treatment was carried out by washing and subsequent drying with cooled air at a temperature of 6°C. The next stage was cutting the half-carcass into separate cuts. Then, the meat was deboned, gutted, and cleaned.

For the production of small-piece semi-finished beef products, muscle tissue trimmings from the tenderloin, thick and thin edges, as well as from the internal and upper muscles of the hip part of the carcass were used. The resulting raw material was cut into pieces about 2 cm thick, subjected to mechanical softening to a thickness of no more than 0.5 cm, after which it was portioned into bars 3...4 cm long and weighing 5...7 g.

For pork semi-finished products, meat from the neck, scapular, and subscapular zones, as well as from the side and back of the thigh were used. The raw material was cut into cubes weighing 30–40 g. The fat mass should not exceed 10%.

The formed semi-finished products were packed in polymer trays of 1 kg. A sachet with an oxygen absorber was placed in each package, after which it was hermetically sealed. Then the products were cooled and stored at a temperature of –1 to +1°C.

During storage, the pH, moisture retention capacity (MRC), the content of basic macronutrients such as proteins, fats, carbohydrates, and the energy value were determined. Sensory characteristics were additionally evaluated. The obtained data were processed using statistical analysis methods using a personal computer.

Before the start of the research, minced meat was obtained from the experimental meat samples.

The concentration of hydrogen ions was determined using a testo 205 pH meter. The pH determination limits were from 0 to 14 units, at a temperature in the range of 0...60°C; step – 0.01 pH units, 0.1°C; error ±0.02 pH, ±0.4°C. The water extract was prepared in a minced meat:water ratio of 1:10. For this purpose, 5 g of minced meat or chopped finished product was taken into a 250 ml conical flask, filled with 50 ml of distilled water, extracted for 30 minutes with periodic stirring. After the end of the extraction, the extract was filtered, and the pH of the filtrate was determined [16].

We determined moisture retention capacity (MRC) in the following order [17]. Samples of minced meat weighing 180...200 g were placed in hermetically sealed containers, weighed, and heated under conditions corresponding to production conditions – boiling in a water bath at a temperature of 78...80°C for 1 hour and cooling in running water to a temperature of 12...15°C. After the end of heat treatment, the containers were opened, the broth and the released fat were poured into weighed aluminum boxes. After removing the broth and fat, the minced meat was soaked with filter paper and weighed. The boxes with broth were placed in a drying cabinet and dried to a constant mass at a temperature of 103...105°C. The mass fraction of moisture released during the heat treatment of minced meat and the moisture holding capacity of minced meat were determined.

The moisture retention capacity was calculated from the following formula, % to the mass of minced meat

$$WHC = W - \frac{m_{b1} m_w}{m_{b2} m} \cdot 100, \quad (1)$$

where W is the mass fraction of moisture in minced meat, %;

m – mass of minced meat sample, g;

m_w – mass of moisture in the test broth, g;

m_{b1} – mass of separated broth and fat, g;

m_{b2} – mass of the test broth with fat, g.

The mass fraction of moisture was determined by drying the product in a drying oven at a temperature of 130°C. The method is based on the ability of the studied product, placed in a drying oven, to give off hygroscopic moisture at a certain temperature [18].

The mass fraction of protein was determined by the Kjeldahl method [19]. This method is based on the mineralization of the sample according to Kjeldahl, distillation of ammonia into a solution of sulfuric acid with subsequent titration of the studied sample.

Mineralization was carried out by heating the sample with concentrated sulfuric acid in the presence of a sulfate-copper mixture. The ammonia formed reacted with an excess of concentrated sulfuric acid and formed ammonium sulfate

$$2NH_3 + H_2SO_4(k) \rightarrow (NH_4)_2SO_4.$$

To determine the amount of ammonia ammonium sulfate, concentrated sodium hydroxide is decomposed

$$(NH_4)_2SO_4 + 2NaOH \rightarrow 2NH_3 + 2H_2O + Na_2SO_4.$$

The resulting ammonia is absorbed by the sulfuric acid solution during titration

$$2NH_3 + H_2SO_{4k} \rightarrow (NH_4)_2SO_4.$$

The excess sulfuric acid was titrated with sodium hydroxide and the amount of bound acid was used to calculate the amount of absorbed ammonia or the amount of nitrogen corresponding to it.

The mass fraction of total nitrogen (X), %, was determined from the following formula

$$X = \frac{\left[0{,}14 \cdot \left(V_1 - V_2\right)\right]}{m}, \quad (2)$$

where m is the mass of the sample, g;

V_1 is the volume of acid (0.1 N) spent on titration of the test sample, cm^3;

V_2 is the volume of acid (0.1 N) spent on titration of the control sample, cm^3.

The mass fraction of total protein (X_i), %, was calculated from the following formula

$$X_i = 6{,}25X, \quad (3)$$

where 6.25 is the conversion factor for protein.

The mass fraction of fat was determined by a method based on repeated extraction of fat from a dried sample with a volatile solvent followed by removal of the solvent and drying of the extracted cartridge to a constant mass [20]. Extractions were carried out in a Soxhlet apparatus, using dichloroethane as a solvent. A sample of the product, dried in a drying oven to a constant mass, was transferred to a paper cartridge. The cartridge with the sample was weighed and placed in the extractor of the Soxhlet apparatus. The extraction duration was 4...6 hours. The mass fraction of fat in the initial sample was calculated from the following formula

$$X = \frac{m_1 - m_2}{m_0}, \quad (4)$$

where X is the fat content, %;

m_1 is the mass of the sleeve with the sample before extraction, g;

m_2 is the mass of the sleeve with the sample after extraction, g;

m_0 is the mass of the sample before drying, g.

Carbohydrate content was determined as the sum of sugars, starch, and dietary fiber, which were determined according to standard methodologies [17, 21, 22].

The energy value of meat products was calculated based on the content of the main macronutrients such as proteins, fats, and carbohydrates. To determine the calorie content, standard conversion factors were used according to the Atwater-Bryant method: 4.0 kcal/g for proteins and carbohydrates and 9.0 kcal/g for fats [23].

The following formula was used for the calculation

$$E = 4\sum P + 9\sum F + 4\sum C, \quad (5)$$

where $\sum P$ is the total protein content, %,

$\sum F$ – total fat content, %,

$\sum C$ – total carbohydrate content, %,

4.0, 4.0 – coefficient for calculating energy value for proteins and carbohydrates, 9.0 – for fats, kcal.

Sensory evaluation of semi-finished product samples was carried out using analytical methods, in particular quantitative descriptive and profile analysis methods [24]. The integral qualitative characteristic was determined on the basis of a point evaluation system (maximum score – 5.00).

Evaluation of organoleptic characteristics of meat semi-finished products made from natural pulp in the form of small-piece semi-finished products involved the analysis of such indicators as appearance, color, smell, consistency, and, if necessary, taste properties. Additionally, the condition of the surface and uniformity of cutting were taken into account.

At the initial stage of our study, consumer packaging was opened with subsequent recording of the product temperature. Next, an assessment of the appearance was carried out, which included a visual check of the uniformity of the shape and size of the pieces, the absence of foreign impurities (bone fragments, blood clots, connective tissue). The surface was also inspected for dirt, slime, or stains – the surface had to be clean, smooth, and natural for the meat of the respective type.

The color was assessed taking into account the typical color range for beef or pork, noting possible deviations, in particular darkening or spotted areas.

The aroma was examined immediately after opening the package: its qualitative characteristics had to correspond to the smell of fresh meat, without foreign, sour, musty, or putrid notes.

To assess the consistency, a spatula was used: in the case of proper product quality, a rapid recovery of shape after deformation should be observed, indicating the preserved elasticity of the tissues.

Taste determination was not carried out within the framework of our studies since the samples did not undergo culinary processing. The surface of the meat should be dry or slightly moist, without mucus, ice formations (in the case of chilled samples), bloody traces, or other defects.

Organoleptic observations were carried out on the 10th and 14th day of storage, which was due to the established increase in the pH level, which could affect the quality of the product.

Based on the results of the organoleptic assessment, conclusions were drawn regarding the quality of semi-finished products and their possible shelf life.

5. Results of research on the effectiveness of packaging with an oxygen absorber during storage of natural meat small-piece semi-finished products

5. 1. Changes in the pH of meat small-piece semi-finished products during storage

According to the research methodology, the raw materials for the production of natural small-piece semi-finished products were chilled beef and pork. The results of determining the initial pH level of meat raw materials, as well as changes in this indicator during storage are shown in Fig. 1.

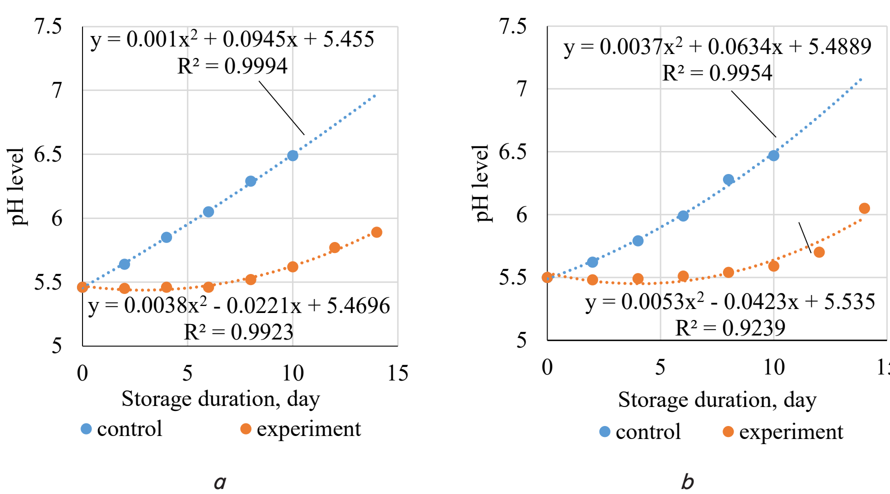

Fig. 1. Regression models of the dependence of the pH level of meat semi-finished products on the duration of storage: *a* – beef semi-finished products; *b* – pork semi-finished products

The results shown in the above figure demonstrate that on the sixth day of storage, the pH level in the samples of the control variants, regardless of the type of meat, reached a critical value of 6.0, indicating the beginning of spoilage processes. Along with this, in the experimental samples from beef, the pH value remained practically unchanged until the sixth day of storage, remaining at the level of 5.46. Its further increase occurred more slowly than in the control variant. In pork semi-finished products, the dynamics of pH growth turned out to be even less intense: by the 10th day the indicator increased by only 1.6%. The pH value, indicating potential spoilage (6.0), was recorded in products of both types only on the 14th day of storage. Mathematical models built on the results of the research demonstrate a high quality of statistical correspondence to actual observations (R^2 = 0.9239–0.9994). This indicates their suitability for interpreting processes related to pH changes in raw meat during storage.

5. 2. Changes in the moisture retention capacity of small-piece meat semi-finished products during storage

To assess the influence of storage conditions on the MRC of muscle tissue of beef and pork semi-finished products, appropriate studies were conducted. The results of determining the MRC of meat of the control and experimental variants during storage are shown in Fig. 2.

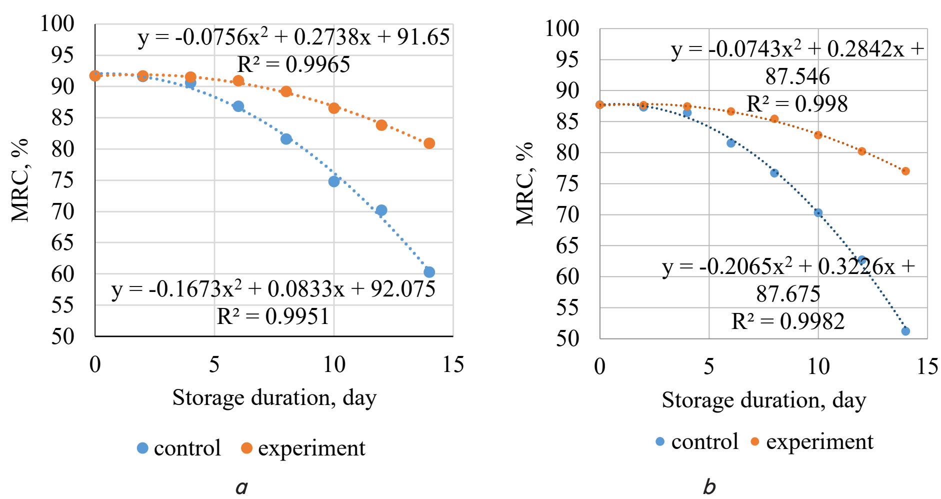

Fig. 2. Regression models of the dependence of the moisture-retaining capacity of natural meat semi-finished products on the duration of storage: *a* – beef; *b* – pork

The constructed mathematical models demonstrated a high level of accuracy in approximating empirical data, which is confirmed by the value of the coefficient of determination R^2 in the range of 0.9951–0.9982. This indicates their statistical reliability and analytical suitability for describing and predicting the dynamics of changes in the moisture retention capacity of meat semi-finished products during storage.

The results of the studies shown in Fig. 2 confirm that the use of hermetic packaging with an oxygen sorbent has a noticeable effect on the MRC of natural meat semi-finished products, regardless of the type of meat raw material. The highest MRC values were recorded during the packaging of samples, which was performed 24 hours after slaughter, which is due to the presence of a high concentration of active protein molecules capable of effectively binding moisture.

During storage, a gradual decrease in MRC was observed in all studied samples, regardless of the type of meat and packaging conditions. However, the rates of this decrease differed significantly between the control and experimental variants. In the control samples, a slight deterioration of MRC was recorded on the fourth day, which is associated with the initial processes of protein denaturation and pH fluctuations. After the sixth day, the changes became more pronounced, especially in pork samples, where more intense degradation of protein structures was observed. Starting from the eighth day, the decrease in MRC significantly accelerated, possibly due to the activation of microbiological processes and the breakdown of protein compounds. From the tenth day, moisture loss became obvious, and by the fourteenth day, a significant deterioration in the hydrophilic properties of tissues was established, which was accompanied by a loss of juiciness and a decrease in consumer characteristics.

In the experimental samples stored under conditions of packaging with an oxygen sorbent, the dynamics of changes in MRC were much slower. Until the eighth day of storage, the indicator remained stable, which is associated with the preservation of the structural integrity of protein components and the optimal pH value within 5.4...5.8. During further storage, only a slight decrease in MRC was observed.

The average level of MRC decrease in the control variants was 34.2% for beef semi-finished products and 41.6% for pork. In the experimental variants, the corresponding values were significantly lower – 11.8% and 12.2%, respectively. It is worth noting that in all variants of the experiment, the MRC of pork semi-finished products was slightly lower compared to beef, which is explained by the higher content of intercellular fat, which is able to displace moisture from the tissue structure.

In order to quantitatively interpret the influence of acid-base balance on the moisture retention capacity (MRC) of semi-finished meat products, mathematical modeling methods were applied, which made it possible to establish a functional relationship between the pH value and the hydrophilicity of tissues. In particular, the constructed regression models reflect the nature of changes in MRC in response to fluctuations in acidity and allow us to predict moisture losses under different storage conditions of products (Fig. 3).

All obtained mathematical models are characterized by high accuracy; the coefficient of determination R^2 within 0.9785...0.9934 indicates the reliability and adequacy of the constructed equations for predicting changes in the moisture retention capacity of meat according to the level of acidity during storage.

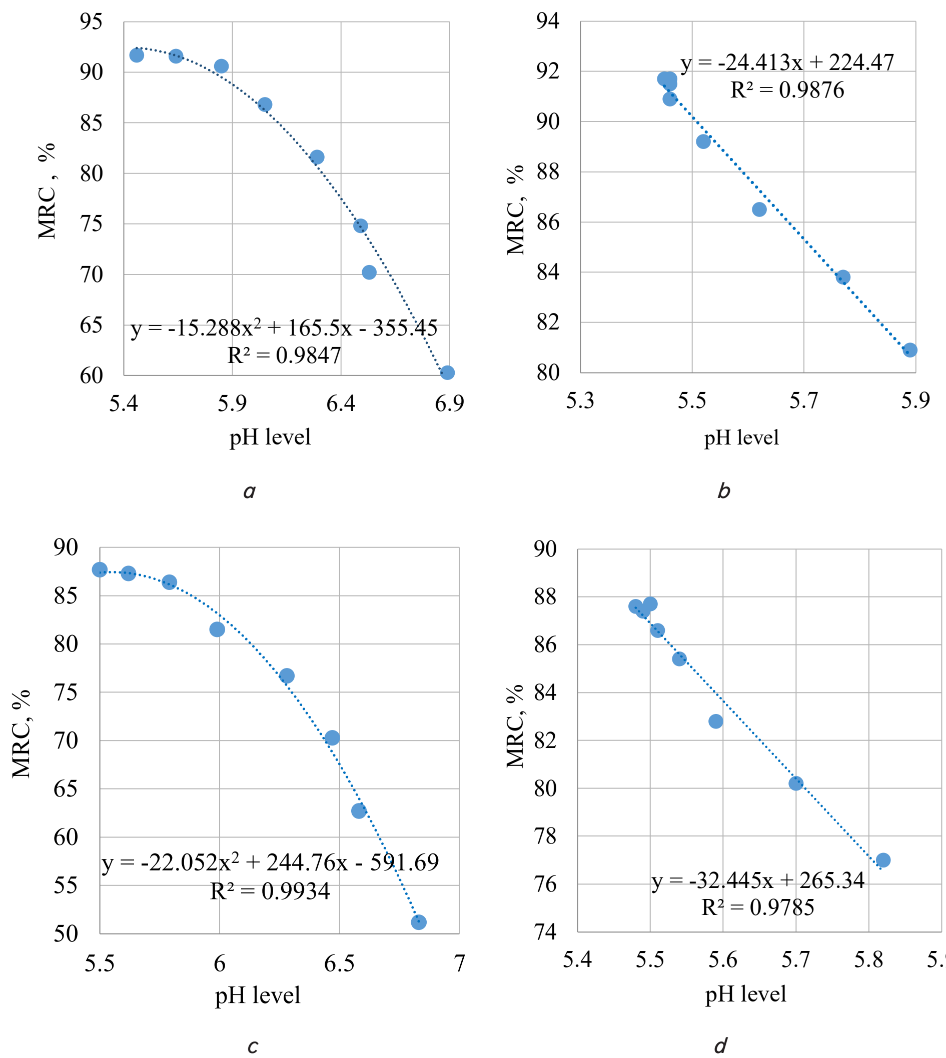

Fig. 3. Regression models of the dependence of pH level and MRC of semi-finished products during storage: *a* – beef control; *b* – beef experiment; *c* – pork control; *d* – pork experiment

5. 3. Changes in the main macronutrients of meat small-piece semi-finished products during storage

During the storage process, profound biochemical transformations occur, which can lead to the degradation of protein structures, lipid oxidation, and changes in the carbohydrate composition. Such changes not only affect the organoleptic characteristics and safety of the product but are also directly related to fluctuations in its energy value.

The determination of these indicators makes it possible to accurately assess the thermal suitability of meat products, predict their consumption dates, and justify the feasibility of using various technological approaches to packaging. The energy value of meat semi-finished products, which is formed mainly due to proteins (4 kcal/g) and fats (9 kcal/g), is an important criterion for assessing their nutritional value in the consumer's diet. That is why monitoring changes in macronutrients during storage is necessary both in scientific research and at the stage of implementing innovative packaging methods and extending shelf life.

The content of the main macronutrients in semi-finished products of the control and experimental variants during storage is given in Table 1.

Table 1

Macronutrient content in semi-finished beef and pork products depending on storage conditions and duration, %

Storage conditions	Shelf life, days	Proteins, %	Fat, %	Carbohydrates, %
Beef				
Fresh meat	0	19.51±1.24	8.19±1.15	0.83±0.22
Control	10	18.63±2.16	8.72±1.06	1.05±0.15
Control	14	17.92±2.35	9.14±2.24	1.34±0.09
Experiment	10	19.14±1.45	8.41±1.34	0.89±0.11
Experiment	14	18.81±1.15	8.49±0.98	1.01±0.08
Pork				
Fresh meat	0	17.19±2.36	13.62±0.87	0.74±0.09
Control	10	16.32±3.14	14.24±1.33	0.93±0.12
Control	14	15.71±3.58	14.63±1.45	1.24±0.21
Experiment	10	16.88±4.12	13.89±1.45	0.79±0.08
Experiment	14	16.63±2.35	14.02±1.23	0.91±0.20

The data above (Table 1) indicate that during the storage of small-piece meat semi-finished products, significant changes occur in the composition of the main macronutrients, which depend on the presence or absence of an oxygen sorbent in the package.

Analysis of protein content revealed that fresh beef (before packaging) contained 19.5% protein. However, after 10 days of storage without the use of an oxygen sorbent, the protein content decreased to 18.6%, and by day 14 – to 17.9%. Such dynamics may indicate the development of active proteolysis processes caused by the action of endogenous enzymes and microorganisms in the presence of oxygen. At the same time, the use of packaging with an oxygen sorbent allowed us to significantly slow down the loss of protein compounds: on the 10th day of storage, the protein content in such packaging was 19.1%, and on the 14th day – 18.8%, i.e., the losses were 0.9...1.0% lower than in the control sample. This indicates effective inhibition of oxidative and microbial processes due to a decrease in the oxygen concentration in the internal environment of the packaging.

In the case of pork, the initial protein content was 17.2%, which is typical for meat with a higher intramuscular fat content. After 10 days of storage without an oxygen sorbent, the protein content decreased to 16.3%, and by day 14 – to 15.7%, i.e., the total loss was 1.5%. Under the conditions of using an oxygen sorbent, the dynamics of changes in protein content were less pronounced: by day 10, a decrease was observed to only 16.9%, and by day 14 – to 16.6%. Thus, the protein loss was only 0.6%, which is almost three times lower than in the control sample. Thus, our data clearly demonstrate that the use of an oxygen sorbent in the packaging of semi-finished meat products significantly slows down protein hydrolysis, reduces the intensity of proteolytic changes and, accordingly, contributes to the preservation of the nutritional value of the product throughout the entire storage period.

The initial fat content in beef was 8.2% (Table 1). In the absence of oxygen sorbent, this figure increased to 9.1% by day 14, while under the conditions of using the sorbent, the fat fraction increased only to 8.5%. The established increase in fat content is not a consequence of the actual accumulation of lipids but rather the result of moisture loss, as a result of which the relative concentration of fats in the mass of the product increases. This effect is typical for the storage of products with a natural water-holding potential, especially under conditions of oxygen access, which also enhances the processes of lipid oxidation.

Similar trends were observed in pork, which in its fresh state had a fat content of 13.6%, which is typical for this type of meat, given its higher fat fraction compared to beef. During 14 days of storage without a sorbent, an increase in fat content to 14.6% was noted, while when using an oxygen sorbent, this figure reached only 14.0%. Although the percentage difference in the change in fat content is less pronounced than in the case of proteins, it is important to consider that pork is more prone to lipid oxidation, in particular unsaturated fatty acids, which react quickly with oxygen. This increases the risk of undesirable changes, such as the formation of secondary oxidation products – aldehydes, ketones, peroxides, which negatively affect the taste and aroma characteristics of meat. Thus, a moderate increase in the percentage of fat content during storage is largely explained by product dehydration. However, in samples where no oxygen sorbent was used, lipids underwent significantly more active oxidation, which was accompanied by a decrease in sensory quality, in particular the appearance of foreign odors and flavors, the loss of typical meat aromas and color deterioration. The use of oxygen sorbents is an effective tool in inhibiting these processes, ensuring better preservation of the lipid fraction and organoleptic characteristics of meat during storage. In meat, carbohydrates are represented mainly by glycogen, residual products of muscle glycogenolysis, as well as a number of secondary compounds that are formed as a result of enzymatic and microbiological decomposition of the main muscle components. During storage, a gradual increase in carbohydrate content was recorded in both beef and pork, which may indicate the accumulation of soluble sugars formed as a result of the destruction of glycogen and other intermediate metabolites.

In beef samples without the use of oxygen sorbent, the carbohydrate content increased from the initial level of 0.8% to 1.3% on the 14th day of storage (Table 1). In pork, a similar trend was observed in the range from 0.7% to 1.2%. Such growth rates indicate active microbiological transformation of intracellular substrates, in particular glycogen, with the subsequent accumulation of carbohydrate metabolites. Microorganisms involved in the decomposition of meat tissues are able to metabolize carbohydrate residues and form both volatile and non-volatile fermentation products. Therefore, an increase in the total carbohydrate content can be considered as an indirect marker of microbiological activity and the initial stages of spoilage.

In cases of using an oxygen sorbent, a significant slowdown in the growth of carbohydrate content was observed. Thus, the maximum values on the 14^{th} day did not exceed 1.0% for both types of meat (Table 1). Such dynamics are evidence of effective inhibition of the activity of aerobic microflora and inhibition of enzymatic processes that depend on the presence of molecular oxygen. Reducing oxygen access limits the vital activity of both opportunistic and specifically spoilage microorganisms, which has a positive effect on the stability of the chemical composition of the product as a whole. Thus, the increase in the content of carbohydrates during meat storage is considered as an indicator of microbiological activity, indicating the destruction of muscle glycogen and metabolic restructuring of the tissue. The use of an oxygen sorbent effectively inhibits this process, ensuring better stability of the microbiological and biochemical characteristics of the product.

Table 2 gives the results of calculations of the energy value of natural meat small-piece semi-finished products during storage; formula (5).

Table 2

Energy value of semi-finished beef and pork products depending on storage conditions and duration, kcal

Storage conditions	Shelf life, days	Energy value, kcal
Beef		
Fresh meat	0	155.07
Control	10	157.2
Control	14	159.3
Experiment	10	155.81
Experiment	14	155.69
Pork		
Fresh meat	0	194.3
Control	10	197.16
Control	14	199.47
Experiment	10	195.69
Experiment	14	196.34

Analysis of our data reveals that in samples stored without oxygen sorbent (control), a more pronounced increase in caloric value is observed: in beef – from 155.07 kcal to 159.3 kcal in 14 days, and in pork – from 194.3 kcal to 199.47 kcal. In experimental samples where oxygen sorbent was used, the increase in energy value occurred much slower: by day 14, it was only 155.69 kcal for beef and 196.34 kcal for pork. This indicates that the use of the sorbent contributes to the reduction of moisture loss and the slowing down of oxidative processes, thereby ensuring a more stable chemical composition of the product and control over the growth of its energy value.

5. 4. Changes in organoleptic indicators of meat small-piece semi-finished products during storage

The final results of the sensory evaluation of meat small-piece semi-finished products from beef and pork are given in Table 3.

The organoleptic evaluation of meat semi-finished products indicates a significant influence of storage conditions on the sensory characteristics of the products (Table 3).

In fresh form, both beef and pork had maximum values for all organoleptic indicators, including appearance, color, smell, consistency. The overall impression was assessed – 5 points for each criterion, which corresponds to high quality meat without signs of initial changes.

Table 3

Sensory evaluation of semi-finished beef and pork products depending on storage conditions and duration, points

Storage conditions	Shelf life, days	Sensory assessment by indicators, points					Total points
		Appearance	Color	Smell	Consistency	Overall impression	
Beef							
Fresh meat	0	5.0	5.0	5.0	5.0	5.0	25.0
Control	10	4.0	4.0	3.5	4.0	4.0	19.5
Control	14	3.0	3.0	2.5	3.0	3.0	14.5
Experiment	10	4.5	4.5	4.5	4.5	4.5	22.5
Experiment	14	4.0	4.0	4.0	4.0	4.0	20.0
Pork							
Fresh meat	0	5.0	5.0	5.0	5.0	5.0	25.0
Control	10	4.0	3.5	3.5	4.0	3.5	18.5
Control	14	3.0	2.5	2.0	3.0	2.5	13.0
Experiment	10	4.5	4.5	4.5	4.5	4.5	22.5
Experiment	14	4.0	4.0	4.0	4.0	4.0	20.0

However, already on the 10^{th} day of storage in the control samples without the use of a sorbent, a noticeable decrease in sensory characteristics is observed. The intensity of the smell decreases to 3.5 points for beef and pork, which may indicate the beginning of microbiological spoilage and oxidative processes. The appearance and color lose their saturation, and the consistency becomes less elastic. By the 14^{th} day, these changes deepen: the total score decreases to 14.5 points for beef and 13.0 points for pork. The smell as the most sensitive indicator of quality drops to critical values (2.5 and 2.0 points, respectively), which is unacceptable for sale or consumption. Unlike the control samples, in the experimental samples using an oxygen sorbent, the deterioration of sensory properties occurs much more slowly. Even on the 14th day of storage, the scores remain at the level of 4.0 points for all indicators, which indicates satisfactory quality and the absence of significant changes in the organoleptic profile. The sorbent demonstrates the greatest positive effect in preserving odor and consistency, which is explained by a decrease in the intensity of fat oxidation and possible inhibition of the development of microflora under conditions of reduced oxygen content in the package.

6. Discussion of results based on studying the effectiveness of packaging with an oxygen absorber during the storage of natural meat small-piece semi-finished products

Our research results provide a thorough analysis of the influence of storage conditions, in particular the use of oxygen sorbents, on the main quality indicators of natural meat small-piece semi-finished products from beef and pork. The study covers the dynamics of pH, moisture retention capacity (MRC), changes in macronutrient composition, and organoleptic characteristics, which allows us to draw comprehensive conclusions regarding the optimal storage terms and conditions.

The change in pH level is one of the key indicators characterizing the quality of meat raw materials. During refrigerated storage of meat, the dynamics of pH depend on the initial characteristics of the product, storage conditions, in particular temperature regime, relative humidity level, and type of packaging, as well as storage duration. Exceeding pH above 6.0 usually indicates the development of spoilage processes, which makes the product unsuitable for consumption. After slaughter of an animal, active glycolysis occurs in muscle tissue, which is accompanied by the accumulation of lactic acid. As a result, the pH value decreases from 7.0–7.2 (typical for the blood of a living animal) to 5.4...5.8. This level is considered physiologically stable and favorable for storage as it inhibits the development of the vast majority of pathogenic microorganisms. During the ripening of meat, the pH value stabilizes within 5.4...5.8, which is optimal for the course of autolytic processes. During this period, the enzymatic activity of tissue enzymes contributes to the hydrolysis of protein and fat compounds, which has a positive effect on the organoleptic characteristics of the product. However, with prolonged storage, especially at temperatures above 0°C, the pH tends to increase. After more than 14 days of storage, a significant increase in the indicator occurs (above 6.5), which, in particular, is observed when the optimal temperature regime is violated [25].

The results of our study fully correlate with the data reported in the scientific literature. It was established that regardless of the type of meat raw material, under storage conditions in conventional packaging without an oxygen sorbent (control option), an increase in the pH level is observed starting from the first day (Fig. 1). This is explained by the further progress of proteolytic processes, which are accompanied by the formation of alkaline metabolites, such as ammonia and other nitrogen-containing compounds. An additional factor is the activity of aerobic microflora, which remains viable at temperatures from minus 1 to 1°C, contributing to the decomposition of organic matter with the formation of alkaline products. In contrast, the use of an oxygen sorbent significantly stabilized the pH level, keeping it in the optimal range for up to 14 days of storage. Thus, the use of hermetic packaging with an oxygen sorbent contributes to maintaining a stable acid-base balance (pH within 5.4...5.9) for up to two weeks of storage (14 days) regardless of the type of meat raw material. Under such conditions, hydrolytic changes in protein compounds are significantly slowed down, in contrast to storage without a sorbent, where contact with air oxygen activates aerobic processes and accelerates quality loss.

Moisture retention capacity (MRC) is another key characteristic of meat quality, reflecting its ability to retain intracellular moisture under the influence of external factors such as thermal treatment, mechanical impact, or long-term storage. This indicator significantly affects the technological suitability of meat raw materials, determines the economic efficiency of production, and is also directly related to the organoleptic properties of the finished product [26].

A high level of MRC ensures proper juiciness of meat after cooking, which is an important component of its taste appeal. On the other hand, a decrease in this indicator leads to excessive release of meat juice during storage or heat treatment, which negatively affects the texture, causes dryness and stiffness of the product, worsening its consumer properties. The functional ability to retain moisture is largely determined by the content and structural integrity of protein compounds that form a hydrophilic network in muscle tissue. In fresh meat, proteins retain their native structure, which contributes to high MRC. With a decrease in the biological activity of protein molecules, in particular due to their denaturation or degradation, the MRC of meat decreases noticeably. Changes in MRC during storage are caused by a number of physicochemical processes, such as disruption of protein bonds, pH fluctuations, and the development of oxidative reactions. Particularly intense changes are observed when the recommended temperature parameters are not observed, which accelerates the destruction of protein structures and reduces their ability to retain moisture [27].

The results of our study related to changes in the moisture retention capacity of meat during storage (Fig. 2) demonstrate that control samples packaged without oxygen sorbent showed the first signs of deterioration of this indicator already on the 4^{th}–6^{th} day of storage. This correlates with the data reported in [28], which indicates that in modified packaging with a high oxygen content, intensive protein denaturation occurs, which leads to moisture loss after 5–7 days of storage. Thus, the early degradation of protein structures (Table 1) in the control variants is explained by an increase in the activity of enzymes and oxidative processes, which are accelerated in the presence of oxygen. At the same time, the experimental samples with oxygen sorbent demonstrated a much slower decrease in the MRC: stability up to the 8th day and minimal losses up to the 14th day.

A feature of our proposed solution is the combination of the tightness of the packaging and the absorption potential of the sorbent. Owing to this combination, the environment inside the package remains stably low in oxygen even with microscopic leaks, unlike vacuum or modified atmosphere without an active component, where oxygen quickly accumulates. This enables prolonged preservation of the hydrophilic properties of proteins and inhibits the transfer of free water. This statement is confirmed by the data obtained (Fig. 2), in particular, by the difference in the decrease in MRC of 31.4–36.5% (control) versus 10.7–10.8% (experimental), which is a clear demonstration of the synergistic effect of hermetic packaging and the sorbent.

The established nature of mathematical dependence between the pH level (x) and the moisture retention capacity (y) indicates differences in the stability of the technological properties of meat semi-finished products depending on storage conditions (Fig. 3). In the control samples without oxygen sorbent, a nonlinear (quadratic) regression dependence is observed, demonstrating a complex mechanism of the influence of acidity on protein structures, with the presence of a pronounced maximum, which corresponds to the optimal pH for preserving MRC. This form of dependence indicates the tendency of these systems to rapid loss of water-holding properties when the pH shifts to the acidic or alkaline side. In contrast, in the experimental samples packaged using oxygen sorbent, a linear nature of the MRC change with a clearly pronounced negative correlation is observed, which is a sign of more predictable and controlled storage conditions, under which protein denaturation and loss of moisture-retention capacity occur gradually. The use of the sorbent effectively inhibits oxygen-dependent autooxidation processes, inhibits the growth of microflora, reduces the rate of pH shift, and, as a result, contributes to the prolonged preservation of the structural and functional properties of meat raw materials.

A comparative analysis of beef and pork revealed that pork is more sensitive to changes in the acidity of the environment, which is manifested in higher values of the coefficients for the independent variable (pH) in the regression equations, which confirms its greater susceptibility to loss of MRC (Fig. 3). At the same time, beef demonstrates a more stable response to pH fluctuations, due to a denser protein structure, a higher concentration of actomyosin complexes, and a lower content of intramuscular fat.

In general, our findings coincide with the world practice of managing MRC through pH regulation but add a new dimension – the role of active oxygen control. This is consistent with the results reported in [29], which showed that pH and ionic strength determine the amount of moisture retention in meat systems, but emphasize that oxygen control is a key factor when working with real meat products.

Analysis of changes in the content of proteins, fats, and carbohydrates revealed patterns that correlate with changes in pH and MRC. The decrease in the content of proteins in samples without sorbent – up to 17.9% (beef) and 15.7% (pork) on the 14th day (Table 1) – indicates a significant activity of proteolytic enzymes and microorganisms in the presence of oxygen. At the same time, only a slight degradation of protein structures – up to 18.8% and 16.6%, respectively – in samples with oxygen sorbent indicates a decrease in the rate of these processes. This is consistent with the results reported in [30], in which the use of oxygen sorbent led to a decrease in proteolytic changes and prolongation of storage times.

As for the fat fraction, the increase in its percentage content in the control samples (up to 9.1% and 14.6%) may be the result of dehydration (Table 1). At the same time, in samples with sorbent, the indicator increased only to 8.5% and 14.0%, which is associated with a lower level of moisture loss and a higher MRC indicator. In addition, in packaging options using traditional methods, intensive lipid oxidation is observed already on the 10^{th}–14^{th} day, which is accompanied by the appearance of secondary signs of spoilage, in particular foreign tastes and odors (Table 3). The use of oxygen sorbent significantly reduced the level of peroxidation of fats and ensured the preservation of the sensory quality of the product at a stable level for a longer time (Table 3).

From the changes in the carbohydrate composition, it is clear that the level of increase in their concentration was 1.3% and 1.2% (beef and pork, respectively) when stored without an active sorbent. This may be due to the significant metabolic activity of the microbiota. In contrast, in samples with a sorbent, this increase was limited to 1.0%, which emphasizes the ability of the packaging system to inhibit enzymatic and bacterial glycogenolysis processes. Such results are confirmed in the literature [3, 31].

Comparison with similar studies confirms that the proposed system is significantly more effective than vacuum or modified packaging without a sorbent, in which protein losses often exceed 2–3% in 14 days and early signs of lipid oxidation are recorded [32, 33]. In contrast, an oxygen sorbent provides losses of up to 1–2%, is safe, does not involve the use of artificial preservatives, and maintains the natural properties of meat.

Our study findings clearly indicate the benefits of using hermetic packaging with an oxygen sorbent to extend the shelf life of semi-finished meat products. The maximum allowable shelf life without a sorbent is 10 days, with 5–6 days being optimal. With the use of a sorbent, this period can be safely extended to 14 days without significant loss of quality, which has significant practical benefits for the food industry and consumers.

Thus, our solutions partially resolve the issue within the framework of those aspects that are directly related to the most labile biochemical and sensory indicators of meat semi-finished products. In particular, it can be argued that it is the mechanism of active oxygen sorption that has become the critical factor due to which it was possible to achieve a positive effect: reducing the rate of oxidative processes and extending the shelf life of meat semi-finished products. Thus, the introduction of packaging with an oxygen sorbent as a technological solution directly responds to the challenges outlined in the problem statement and proves its relevance for the storage of small-piece meat semi-finished products, which are particularly sensitive to oxidative spoilage.

Therefore, the results of our study could become the basis for improving the storage technologies of small-piece natural meat semi-finished products by introducing active packaging elements, in particular oxygen sorbents.

However, our results are valid within the specified experimental conditions and should be considered taking into account a number of limitations. In particular, the study was conducted at a constant temperature (minus 1...1°C); therefore, under other temperature fluctuations or violations of storage conditions, the efficiency of the sorbent may differ significantly. In addition, the work was focused only on certain types of products such as small-piece natural semi-finished meat products from beef and pork. The behavior of other types of meat products, in particular those containing a different amount of proteins and fats, as well as spices, antioxidants, or stabilizers, requires a separate study. At the same time, a specific type of packaging material with a high level of oxygen barrier was used. Changing the polymer base may lead to changes in sorption dynamics and, accordingly, affect the results.

Regarding the shortcomings, we should note the lack of an economic assessment of the introduction of sorbent into industrial production, which complicates the analysis of the profitability of this technology.

Therefore, the implementation of the research results in practice should be accompanied by taking into account the established limitations and eliminating the identified shortcomings through further studies, including the economic component.

Further investigation of the mechanisms behind the influence of these components on oxidation processes, microbiological stability, and preservation of sensory characteristics would allow us to devise scientifically based recommendations on optimal packaging conditions. This, in turn, could contribute to improving the safety and quality of products, extending their shelf life without the use of synthetic preservatives, as well as meeting consumer needs for high-quality and natural food products. It is also promising to expand research to other groups of animal food products in order to design universal adaptive active packaging systems.

7. Conclusions

1. The results of our studies show that the use of hermetic packaging with an integrated oxygen sorbent enables stabilization of the pH level within 5.4...5.9 during 14 days of storage, regardless of the type of meat raw material. In samples without the use of the sorbent, a more intensive increase in pH was noted, which is due to contact with atmospheric oxygen.

2. Analysis of the moisture retention capacity has revealed that beef has a higher MRC compared to pork. This is explained by the lower fat content in beef, which contributes to better moisture retention in muscle fibers. In pork, due to its higher fat content, a more intensive loss of MRC is observed, with a particularly sharp decrease in control samples after 5...7 days of storage. In experimental variants with oxygen sorbent, this indicator remained at a high level even for 14 days. It was established that the MRC of muscle tissue is an integral indicator of its functional and technological state, which reflects the depth of the internal biochemical processes caused by storage conditions. The regression analysis established the presence of a close feedback between the pH value and MRC, which is confirmed by high coefficients of determination ($R^2 = 0.9785–0.9934$), which makes it possible to predict changes in the water-binding capacity of semi-finished products based on acidity values. The regression equations built reflect the specificity of changes depending on the type of raw material and storage conditions: in the control samples, a nonlinear decrease in MRC was observed, while in the experimental ones, predominantly linear dynamics with a significantly lower rate of degradation were observed.

3. The decrease in protein content during storage was more pronounced in samples without sorbent, which indicates more intensive proteolytic processes. The fat component, on the contrary, showed a slight increase in percentage terms due to moisture loss, but was accompanied by the risk of oxidation, especially under control conditions. The content of carbohydrates, mainly represented by glycogen residues, also increased, which is an indirect marker of microbial tissue decay. In the presence of oxygen sorbent, this increase was more restrained. The energy value of meat samples increased over time under control storage conditions due to dehydration and an increase in fat concentration. In experimental samples with a reduced presence of oxygen, changes in energy value were minimal, which confirms the stability of nutritional value under optimized conditions.

4. It was found that the first signs of deterioration in the quality of the experimental samples of semi-finished products were observed only on the 14th day of storage, and the degree of these changes was significantly lower compared to the control samples, in which significant quality violations were recorded already on the 10th day. By the 14th day, the control samples

showed non-compliance with a number of critical parameters, which became the basis for their exclusion from further research. Summarizing the results of the organoleptic evaluation, as well as changes in physical-chemical parameters (pH and MRC), it can be stated that the maximum permissible storage period of natural meat small-piece soft semi-finished products in hermetic packaging without an oxygen sorbent at a temperature of –1 to +1°C should not exceed 10 days. The optimal storage period from the point of view of pH stability and MRC preservation is 5–6 days. Under similar conditions, but with the use of an oxygen sorbent, the safe storage of semi-finished products can be extended to 14 days without significant loss of quality.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

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

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