

This study investigates the quality of minced meat products (beef steaks) fortified with a nanostructured food additive of the combined composition "Laminaria + NPFe₃O₄". The task addressed is to stabilize the polyphase structure and improve the consumer properties of minced meat products. It was found that introducing the additive in the amount of 0.1–0.3% improves the taste, aroma, and consistency of steaks, contributes to the formation of a more saturated and natural color, as well as increases the hardness, plasticity, elasticity, and chewiness of the products. With the introduction of the "Laminaria + NPFe₃O₄" food additive, the brightness of the products decreased by 1.02–1.06 times, and the b* and H* indicators increased by 1.16–1.42 and 1.08–1.43 times, respectively. The optimal concentration of the additive was determined to be 0.2%.

The regularities in the influence of the nanostructured food additive of the combined composition "Laminaria + NPFe₃O₄", which combines components of brown algae *Laminaria* sp. and nanoparticles of iron oxide NPFe₃O₄, on the properties of beef steaks (on the transformation of pigments, the formation of textural characteristics, and sensory profile) have been established. The synergistic nature of the action of the additive components, which provides a comprehensive effect on the quality characteristics of minced meat products, has been shown, and its rational concentration at the level of 0.2% of the mass of the recipe mixture has been justified.

The scope of practical application of the results includes the technology of manufacturing minced meat products. The expected effects of the implementation of the NFACC "Laminaria + NPFe₃O₄" are the improvement of organoleptic and textural characteristics of products and the expansion of the range of functional meat products with increased biological value

Keywords: "Laminaria + NPFe₃O₄" food additive, minced meat products, quality assessment, food supply for the defense forces

DETERMINING THE QUALITY OF MINCED MEAT PRODUCTS MANUFACTURED WITH THE USE OF THE FOOD ADDITIVE "LAMINARIA+NPFE₃O₄"

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1. Introduction

One of the priority tasks of contemporary food science is to provide people with food products that not only satisfy the energy needs of the body but also contribute to

the prevention of nutritionally dependent diseases and the correction of essential nutrient deficiencies. According to current research, unbalanced diets are accompanied by an insufficient intake of minerals, dietary fiber, and other biologically active compounds, which causes an increase

in interest in designing functional food products with increased biological value [1].

Meat products occupy an important place in the structure of people's diet as a source of complete protein, essential amino acids, and minerals. At the same time, the modern concept of healthy nutrition involves the development of meat products that can provide additional physiological effects by introducing functional ingredients of natural origin [2]. The practical implementation of such an approach contributes to the expansion of the range of products for preventive purposes and the increase of their nutritional and biological value.

A promising direction for improving the technologies of functional meat products is the use of seaweed. It has been proven that seaweed is a source of polysaccharides, minerals, dietary fiber, and biologically active compounds that exhibit antioxidant and functional-technological properties and can also positively affect the structural characteristics of food systems [3]. In addition, the use of seaweed in meat technologies contributes to an increase in moisture retention capacity, a decrease in losses during heat treatment, and an improvement in the stability of finished products [4].

An equally relevant area in the evolution of food technologies is the use of nanoscale forms of mineral components. It has been established that iron nanoparticles are characterized by increased bioavailability and could be effectively used to fortify food products with iron without significant deterioration of their organoleptic properties [5]. The use of nanocomponents opens up prospects for designing products with improved nutrient digestibility and specified functional and technological properties [6]. The prospects for the use of functional ingredients in the technology of meat products are confirmed by the results of studies on the use of structure-forming agents, hydrocolloids, and other stabilizing components, which provide increased moisture retention capacity, regulation of textural characteristics and reduction of technological losses of products [7]. It has also been established that nanoscale iron-containing components can improve the functional and technological properties of meat systems, increase the yield of finished products, and exhibit antioxidant properties [8]. Studies of combined functional additives based on natural components and iron nanoparticles demonstrate the possibility of simultaneously increasing the biological value and improving the structural and mechanical characteristics of food products [9]. In addition, the use of such ingredients in various food systems contributes to the improvement of rheological properties, structural stability, and consumer characteristics of the finished product [10].

Of particular scientific and practical interest is the combination of natural biologically active components of seaweed with nano-sized mineral ingredients in the composition of combined food additives. This approach potentially makes it possible to solve several tasks simultaneously: increasing the nutritional and biological value of products, improving their structural-mechanical and organoleptic characteristics, reducing technological losses, and expanding the range of functional meat products.

Therefore, it is a relevant task to devise and substantiate the use of combined functional ingredients based on seaweed and nano-sized mineral compounds (in particular iron) in meat product technologies both from the standpoint of nutrition and food safety, and from the standpoint of increasing the efficiency of modern meat processing technologies and designing functional products with improved consumer properties.

2. Literature review and problem statement

Meat products are an important source of complete animal protein, essential amino acids, and minerals; however, the segment of functional meat products remains underdeveloped. Of particular interest are nanostructured food additives, which, due to their high specific surface area and reactivity, are able to modify the properties of food systems and increase the bioavailability of nutrients. Work [1] investigated the use of a nanostructured food additive of combined composition in the technology of rye-wheat bread. It was shown that the combination of kelp with a nanosized iron-containing component increases the bioavailability of biologically active substances and exhibits structure-forming, moisture- and fat-retaining, sorption, and stabilizing properties. However, the specificity of the functioning of such an additive in meat disperse systems has not been determined, which may be due to significant differences in the mechanisms of structure formation in flour and meat products.

Paper [2] investigated the role of meat and meat products as functional food products. It has been shown that modification of the recipe makes it possible to reduce the content of fat, cholesterol, salt, and other undesirable components and increase the content of biologically active substances. However, the issues of optimizing the technologies for fortifying meat products with functional ingredients and ensuring the stability of their consumer properties have remained unresolved, which may be due to the complexity of the interaction of additional components with the protein-fat matrix of meat systems.

One of the promising areas for improving the technology of meat products is the use of seaweed as a source of biologically active compounds. It has been established that seaweed contains dietary fiber, polysaccharides, minerals, phenolic compounds, and other components that exhibit antioxidant, prebiotic and structure-forming properties. Work [3] summarizes data on the use of seaweed as functional ingredients of healthy nutrition. It has been established that seaweed is a source of proteins, minerals, polysaccharides, dietary fiber, and biologically active compounds with antioxidant and anti-inflammatory properties. However, the issues of the stability of bioactive components and the influence of algae on the consumer characteristics of finished products remain insufficiently studied, which is associated with the complexity of the transformation of their components during technological processing.

The use of micro- and macroalgae in the technology of meat products is analyzed in [4]. It is shown that algae increase moisture retention capacity, reduce losses during heat treatment, and improve antioxidant properties of products. However, the results on the influence of algae on textural, color, and sensory characteristics are contradictory, which is explained by differences in the chemical composition of different types of algae, their dosage, and features of food systems.

Promising food fortifiers are nanoparticles of mineral oxides, in particular iron, which are characterized by high bioavailability and less impact on the organoleptic properties of products compared to traditional iron compounds. Work [5] investigated the use of iron nanoparticles for food fortification and prevention of iron deficiency states. It was shown that nanosized iron compounds are characterized by high bioavailability, better absorption, and less impact on the organoleptic properties of products compared to traditional

iron salts. However, the issues of long-term safety and stability of nanoparticles in food matrices remain poorly studied, which is due to the limited number of studies on real food systems.

Paper [6] investigated the use of food nanocomponents to improve public health and ensure sustainable development of food systems. It was shown that nanotechnologies contribute to the creation of products with improved functional properties and increased bioavailability of nutrients. However, the issue of the influence of nanocomponents on the quality of products during long-term storage remained insufficiently studied due to the difficulty of predicting the behavior of nanostructures in multicomponent food matrices.

In [7], the influence of different classes of stabilizers on the physicochemical properties of a model low-fat meat product was investigated. It was found that the use of starches, vegetable proteins, dietary fibers, and hydrocolloids contributes to the reduction of moisture loss and the regulation of the structural and mechanical characteristics of products. However, the issue of the combined use of stabilizers and their influence on the organoleptic properties of finished products remained insufficiently studied due to the difficulty of predicting synergistic effects between components in multicomponent meat systems.

In work [8], the influence of the food additive “Magne-tofood” (Fe_3O_4) on the physicochemical and functional and technological properties of model minced beef was investigated. An improvement in moisture binding capacity, yield of finished products, protein digestibility, and antioxidant stability of systems was established. It has also been proven that Fe_3O_4 nanoparticles exhibit antioxidant, structure-forming and stabilizing properties, improve water-binding capacity, increase the yield of finished products, and contribute to the formation of more stable dispersed systems. However, mechanisms behind the influence of ferric oxide nanoparticles on the color characteristics and texture profile of finished products have not been investigated, which may be due to the complexity of intermolecular interactions in multicomponent meat systems.

Studies show that the introduction of seaweed into meat systems contributes to an increase in water and fat-holding capacity, a decrease in losses during heat treatment, and an improvement in the textural characteristics of products. In [9], the effect of the complex “Laminaria + NPFe_3O_4 ” food additive on the functional and technological properties of minced meat products was investigated. It was shown that the use of the additive improves organoleptic indicators, structural and mechanical characteristics, increases the yield of finished products, protein digestibility, and resistance to oxidative damage. However, a comprehensive assessment of the color characteristics and textural profile of products after heat treatment was not carried out, which may be due to the focus of research mainly on functional and technological indicators. In [10], effect of the “Laminaria + NPFe_3O_4 ” additive on the properties of rye-wheat bread was investigated. Improvements in dough rheological properties, specific volume, porosity, dimensional stability, and biological value of the finished product were found. However, there is no data on the formation of color and textural characteristics of the product, which may be due to the focus of the study on baking indicators.

In [11], the possibilities of using food nanotechnologies to increase the bioavailability of nutrients and create functional products were investigated. The prospects of using nanoscale

systems for targeted delivery of biologically active substances were shown. However, the issues of stability of nanosystems in food products and the mechanisms of their interaction with components of food matrices remain insufficiently studied.

In [12], food products containing processed, manufactured, or packaged nanotechnological components were investigated. The possibility of using metal nanoparticles, nanoencapsulated vitamins, and liposomal systems to improve the functional properties of products was shown. However, the issues of safety of such systems and their impact on the quality indicators of finished products remain insufficiently studied, which is due to the lack of reasonable long-term experimental data.

In [13], the mechanisms of formation and transformation of micro- and nanoparticles in broth during meat stewing were investigated. It has been shown that during the heat treatment, colloidal nanoparticles are formed and stabilized, which accumulate lipids, Maillard reaction products, nutritional and flavor compounds, playing an important role in shaping the properties of the broth. However, the issues of the influence of micro- and nanoparticles on the organoleptic characteristics of the finished product and their behavior in food systems of different composition remain insufficiently studied, which may be due to the complexity of colloidal processes and the multicomponent nature of food matrices.

In [14], methods of synthesis, surface functionalization, and directions of practical application of magnetic Fe_3O_4 nanoparticles were investigated. It has been shown that the use of various methods of obtaining and modifying the surface makes it possible to regulating the physicochemical properties of nanoparticles and expanding the scope of their application, in particular in catalysis, immobilization of biomolecules, medicine and food technologies. However, the issues of safety of functionalized nanoparticles, their stability in complex biopolymer matrices, and optimization of technologies for use in food products remain insufficiently studied, which may be due to the significant dependence of the properties of nanoparticles on the synthesis technique and the nature of surface modification.

In [15], the synthesis and properties of polysaccharide nanoparticles « $\text{Fe}_3\text{O}_4 \times \text{Fructus mori L.}$ » were studied. It was shown that the formation of nanoparticles of the “core-shell” type provides a reduction in particle size, increased antioxidant activity, and improved bioavailability of polysaccharides compared to the original compounds. It was found that the functional properties of nanosystems are largely determined by the conformation of the particles. However, the mechanisms of biological action, safety, and effectiveness of the use of such nanoparticles in food systems remain insufficiently studied, which may be due to the difficulty of predicting the interaction of nanostructures with components of food matrices and biological systems. At the same time, the authors emphasize the need for further studies on the mechanisms of interaction of iron nanoparticles with components of food matrices, their effect on the textural and color characteristics of products, as well as the assessment of the stability of such systems during technological processing.

In [16], various carotenoid nanoencapsulation systems and their effect on the stability and bioavailability of bioactive compounds were studied. It has been shown that the use of nanoemulsions, liposomes, solid lipid and polymer nanoparticles makes it possible to protect carotenoids from degradation under the influence of light, heat, and oxygen,

increasing the efficiency of encapsulation and controlled release. It has been established that the type of nanostructure significantly affects the physicochemical characteristics of nanosystems, in particular their stability and dispersion. However, the issues of optimizing the parameters of nanocapsule evaluation, scaling technologies for the food industry, and ensuring long-term stability during storage and technological processing remain unresolved, which is due to the complexity of industrial reproduction of nanosystems with specified properties.

In [17], the use of surface-functionalized Fe_3O_4 nanoparticles as the basis of rapid and highly sensitive methods for detecting contaminants in food products was investigated. It has been shown that the combination of superparamagnetic properties and nanoscale effect provides high specificity and efficiency of detection of endogenous and exogenous components. The use of functionalized nanoparticles has been shown to be promising for improving the quality and safety of food products. However, the stability of functionalized nanocomponents in complex food matrices has not been studied in detail, which may be due to the influence of proteins, lipids, and polysaccharides on the surface state and aggregation stability of nanoparticles.

In [18], the effect of different types and concentrations of edible seaweed on the physicochemical and structural-mechanical characteristics of meat gel-emulsion systems with a reduced salt content was investigated. Improvement of water and fat-binding properties and changes in the textural characteristics of the systems were shown. However, the results regarding the effect on color and sensory properties were ambiguous, which may be due to the species characteristics of algae and different concentrations of their introduction.

In [19], the technological and functional properties of meat products fortified with seaweed were investigated. It was shown that the use of seaweed is an effective approach to increasing the nutritional and biological value of products. However, the issue of optimizing recipes and the effect of algae on the sensory characteristics of finished products requires further investigation, which is due to the specificity of the chemical composition of different types of algae.

In addition, some authors have established a positive effect of algae on the antioxidant stability and mineral composition of meat products. In [20], the phenolic composition and antioxidant activity of seaweed extracts were investigated. It was found that the extracts effectively inhibit oxidative processes and may exceed the activity of individual synthetic antioxidants. However, the practical use of such extracts in food technologies has not been studied in detail due to the complexity of ensuring their stability in multicomponent systems.

In [21], the nutritional value of wild and cultivated seaweeds was investigated. It was shown that seaweeds are a valuable source of proteins, minerals, essential amino acids, and phenolic compounds. However, the issues of protein bioavailability and the influence of phenolic components on its digestibility remain to be studied in detail, which may be due to the complexity of the interaction of phenolic compounds with proteins. Therefore, the results of the studies indicate that the effect of using seaweeds largely depends on their type, concentration, and characteristics of the food system. The available literature contains conflicting information on the effect of algae on the color, texture, and sensory perception of meat products.

In [22], the stability of iodine and selenium in functional meat products fortified with seaweed was investigated. It was

found that the preservation of trace elements depends on the type of algae and heat treatment regimes. However, there are no substantiated recommendations on optimal recipes and technological regimes, which is associated with significant variability in microelement losses during different cooking methods.

In [23], the effect of including seaweed on the quality and mineral composition of meat was investigated. It was shown that the use of *Saccharina latissima* contributes to an increase in the content of iodine and selenium and improves the antioxidant properties of the product. However, questions regarding the optimal level of use of algae and the long-term impact on product quality remain unresolved due to the lack of long-term experimental observations.

In [24], the influence of seaweed on the quality and taste characteristics of raw dried meat products was investigated. It was shown that seaweed has a positive effect on color stability and certain product quality indicators. However, the mechanisms of sensory characteristics formation and possible changes in consumer perception of products require further investigation. In addition, the use of brown macroalgae *Laminaria sp.* in complex food additives for the production of minced meat products remains to be studied in detail.

In [25], the potential of seaweeds as sources of prebiotic and antioxidant functional ingredients was investigated. The prospects of using macroalgae for creating health-promoting products were shown. However, the effectiveness of using individual bioactive components in specific food technologies and their physiological effect in the human body were not studied in detail.

In [26], phenolic compounds of seaweeds were investigated as natural antioxidants and functional ingredients. It was established that brown algae phlorotannins are characterized by high antioxidant activity and the ability to interact with proteins. However, the issues of bioavailability of phenolic extracts and the features of their use in food technologies remain to be studied in detail.

In treatise [27], data on the nutritional value of seaweeds and their effect on the human digestive system are summarized. It was shown that seaweeds are a source of dietary fiber, ω -3 fatty acids, essential amino acids, vitamins, as well as structure-forming hydrocolloids. However, the issues of substantiating the formulation composition of food products fortified with brown macroalgae, in particular *Laminaria sp.*, and assessing their impact on the consumer characteristics of the finished product remain insufficiently researched.

A promising approach is the combination of natural biologically active components and nano-sized mineral ingredients in one food supplement. In papers [9, 10] it is shown that the nanostructured food supplement of the combined composition "Laminaria + NPF_3O_4 " has a positive effect on the functional and technological properties of meat and flour products, improving their organoleptic indicators, structural and mechanical characteristics, and biological value. However, the cited studies mainly concerned the general functional and technological properties of food systems and do not contain a comprehensive assessment of the effect of the additive on the formation of color, texture profile, and sensory characteristics of finished meat products after heat treatment.

Thus, our review of the literature shows that the use of seaweed, Fe_3O_4 nanoparticles, as well as combined additives based on them, provides an improvement in the functional and technological properties of food systems and an increase in their biological value. At the same time, there is no compre-

hensive data on the influence of the nanostructured food additive of the combined composition “Laminaria + NPFe₃O₄” on the processes of color formation, pigment transformation, formation of the textural profile, and sensory characteristics of minced meat products after heat treatment. Mechanisms behind the interaction between the additive components and the protein-fat matrix of minced meat systems and the issue of substantiating its rational concentration in the recipe of beef steaks also remain to be studied in detail.

Based on our analysis of literary sources, a scientific task was formulated, which involves establishing the patterns of influence of the nanostructured food additive of the combined composition “Laminaria + NPFe₃O₄” on the formation of color, textural and sensory characteristics of beef steaks and substantiating its rational concentration in the recipe of the finished product.

3. The aim and objectives of the study

The purpose of our study is to determine the quality of minced meat products (beef steaks) made using a nanostructured food additive of combined composition – NFACC “Laminaria + NPFe₃O₄”. This will improve the consumer properties and quality indicators of minced meat products.

To achieve the goal, the following tasks were set:

- to investigate the effect of a nanostructured food additive of combined composition NFACC “Laminaria + NPFe₃O₄” on the sensory properties of experimental samples of beef steaks using the flavor method;

- to investigate the effect of a nanostructured food additive of combined composition NFACC “Laminaria + NPFe₃O₄” on the color characteristics of experimental samples of beef steaks;

- to investigate the effect of a nanostructured food additive of combined composition NFACC “Laminaria + NPFe₃O₄” on the structural and mechanical properties of experimental samples of beef steaks using the texture profile analysis (TPA) method.

4. The study materials and methods

The object of our study is the quality of minced meat products (beef steaks) made using “Laminaria + NPFe₃O₄” – the nanostructured food additive of the combined composition

The principal hypothesis assumes that the use of NFACC “Laminaria + NPFe₃O₄”, the nanostructured food additive of the combined composition, in the recipe of beef steaks could improve their consumer properties and quality indicators. To test the hypothesis, the effect of the additive on the organoleptic, physical, and structural-mechanical characteristics of the finished products was studied.

The study assumed that the components of the nanostructured food additive “Laminaria + NPFe₃O₄” are evenly distributed in the recipe mixture and in the studied concentration range do not cause a negative impact on the quality indicators of the finished products. As a simplification, it is assumed that all other factors shaping the quality of steaks (the composition of basic raw materials, technological process parameters, heat treatment, and storage conditions) are constant, and changes in quality indicators are mainly due to the introduction of NFACC “Laminaria + NPFe₃O₄”.

The following materials were used: iron oxide nanoparticles (Fe₃O₄ NPs) were obtained by the method of co-precipitation of Fe(II) and Fe(III) salts using ammonia solution. The formed precipitate was washed repeatedly with distilled water, after which it was dried at a temperature of 100°C for 60 min. The result was a dark brown powder, which is a mixture of iron oxides FeO and Fe₂O₃ and contains more than 90% iron and about 10% moisture. The average diameter of Fe₃O₄ NPs was 75 ± 10 nm, while the zeta potential value in aqueous suspensions was 40 ± 5 mV. The synthesized Fe₃O₄ NPs are characterized by high stability to the action of environmental factors and oxidation processes [10].

Food powder of kelp (*Laminaria japonica* L.) with a moisture content of less than 12% and a crude protein content of 11.4% was purchased from Fuzhou Beautiful Agricultural Development Co., Ltd. (Fujian, China).

The crushed kelp powder was combined with Fe₃O₄ NPs by mechanical mixing and grinding in a mortar for 3–5 minutes. After that, the resulting mixture was dried at a temperature of 105°C until the moisture content was not higher than 5%. The synthesized nanostructured food additive of the combined composition – NFACC “Laminaria + Fe₃O₄ NPs” – contained 15% (wt./wt.) Fe₃O₄ NPs, and 85% (wt./wt.) kelp powder [10]. The resulting additive was used as a functional ingredient in the technology of minced meat products – beef steaks (Fig. 1).



Fig. 1. Nanostructured food additive of combined composition “Laminaria + NPFe₃O₄”

Industrial beef, chicken eggs, butter, sunflower oil, onion, garlic, table salt, and black pepper (ground) were purchased at supermarkets and local markets in Kharkiv (Ukraine). A traditional recipe was used to make a control sample of beef steaks (control – sample 1). Specifically, beef – 97.0 g; onion – 18.0 g; chicken egg – 8.0 g; table salt – 1.0 g; black pepper – 0.05 g; garlic – 6.0 g; butter – 5.0 g; sunflower oil for frying – 40.0 g. The total mass of the minced meat system was 135.05 g, from which 100.0 g of the finished minced meat product was obtained. In experimental samples (2, 3, 4), a nanostructured food additive of combined composition – NFACC “Laminaria + NPFe₃O₄” – was additionally introduced into the minced meat in an amount of 0.1%, 0.2% and 0.3% (w/w) of the total mass of the mixture. The corresponding variants were designated as sample 2, sample 3, and sample 4.

Minced meat was prepared by grinding beef, onion, and garlic in an industrial meat grinder MIM-300 Arm-Eco (manufactured by “Arm-Eco”, Ukraine). After that, the recipe mixture was mixed with salt, spices (black pepper), NFACC “Laminaria + NPFe₃O₄”, and chicken egg in a minced meat mixer Farshemis Hendi 282670 (manufactured by “Hendi”, Netherlands) for 3–5 min. The resulting mass was kept for

8–10 minutes to stabilize the structure. The heat treatment of the experimental samples of minced meat products (beef steaks) was carried out by the method of basic frying at a surface temperature of (150–160) °C until culinary readiness was achieved, which corresponded to a temperature of (85±1) °C in the center of the product. After completion of the heat treatment, the steaks were cooled at room temperature for 2 hours. Then they were hermetically packaged and stored at a temperature of (4 ± 1) °C for 12 hours before conducting physical, structural, and mechanical studies and sensory evaluation.

To achieve the set goal, generally accepted [1, 6, 9, 28–30] and standardized research methods were used in accordance with the requirements of DSTU 4437:2005, DSTU 4589:2006, as well as modern instrumental approaches to physical and structural-mechanical analysis.

Sensory evaluation of beef steak samples was carried out in accordance with international ISO standards. To build profiles, the methodology set out in DSTU ISO 6564:2005 “Sensory research. Methodology. Methods for creating a flavor spectrum” (ISO 6564:1985, IDT) was used. Tasting evaluation was carried out by an expert board consisting of 8 specialists. During the study, descriptors that have consumer significance and are included in the complex flavor profile of a hypothetical reference sample were analyzed. To evaluate the experimental samples of steaks, respondents were offered 10 descriptors ranked by importance. After tasting and mathematical processing of the results, flavor profiles were formed for beef steaks samples with the addition of a nanostructured food additive of combined composition NFACC “Laminaria + NPF₃O₄”, and a control sample without its addition.

Organoleptic assessment was carried out on a five-point scale of desirability and intensity of manifestation of taste and aromatic characteristics of the product: 0 points – sign absent; 1 point – barely noticeable; 2 points – weak manifestation; 3 points – medium intensity level; 4 points – pronounced manifestation; 5 points – very strong manifestation [28, 29].

Palatability was considered as a complex sensory sensation that is formed in the oral cavity and persists after swallowing, including retronasal perception of aroma. Among the selected descriptors, one was used to evaluate the overall impression (taking into account the correspondence of the characteristics, their intensity and background taste and aromatic characteristics). Six – to characterize taste and aroma. Three – to analyze tactile sensations in the oral cavity, which reflected the consistency properties of minced meat products – beef steaks.

Among the taste descriptors, special attention was paid to the characteristic “harmonious”, which reflects the balance of the product and the optimal combination of its components. Descriptors such as “harmonious”, “inherent”, “meaty”, “weakly pronounced”, “salty”, and “salty-sea flavor” were used to assess the fullness of the taste of beef steaks fortified with NFACC “Laminaria + NPF₃O₄”. During the tasting, the experts first assessed the smell (aroma) of the samples, after which they determined the intensity of the manifestation of individual taste components and analyzed the residual flavor and its stability.

Color was evaluated using a CR-600d D65 colorimeter (Minolta Co., Osaka, Japan) by measuring the CIE-lab parameters L^* , a^* and b^* , where L^* refers to the lightness of the sample (0 = black and 100 = white), a^* to the greenness (– a^*)/redness (+ a^*), and b^* to the blueness (– b^*)/yellowness (+ b^*) [30]. For the measurement, an integrated light

source was placed in the beef steak test sample, and the $L^*a^*b^*$ values were recorded in 8 different areas of each test sample.

H^* , C^* and ΔE^* are derived colorimetric values calculated from the L^* , a^* and b^* coordinates in the CIELAB color space (formulae 1, 2, and 3)

$$H^* = \tan^{-1} \left(\frac{b^*}{a^*} \right), \quad (1)$$

where H^* – hue angle (color tone angle) – characterizes the dominant color shade (red, yellow, green, blue, etc.); a^* – color coordinate on the green (–) ↔ red (+) axis; positive values indicate an increase in the red hue, negative values indicate an increase in the green hue; b^* – color coordinate on the blue (–) ↔ yellow (+) axis; positive values correspond to a yellow hue, negative values correspond to a blue hue

$$N^* = \sqrt{(a^*)^2 + (b^*)^2}, \quad (2)$$

where C^* – color chromaticity – characterizes the intensity, purity, or saturation of the color

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}, \quad (3)$$

where ΔE^* – total color difference – integral indicator of color change between two samples; ΔL^* , Δa^* and Δb^* – indicators of change (increase or decrease) of corresponding color coordinates in CIELAB color space system between control and test samples or before and after technological processing. ΔL^* – change of lightness: $\Delta L^* > 0$ – sample became lighter; $\Delta L^* < 0$ – sample became darker. Δa^* – change of red-green component: $\Delta a^* > 0$ – increase of red hue; $\Delta a^* < 0$ – decrease of redness or shift to green. Δb^* – change of yellow-blue component: $\Delta b^* > 0$ – increase of yellow hue; $\Delta b^* < 0$ – increase of blue hue or decrease of yellowness.

Texture profile analysis (TPA) of beef steak samples was performed using a Stable Micro Systems texturometer (TA-HDi, Surrey, UK) equipped with a 50 kg strain gauge and a cylindrical aluminum probe with a diameter of 36 mm, according to the Born method [10, 28]. Before testing, the samples were cut into 2 × 2 cm cubes and kept for 2 h at a temperature of (20 ± 2) °C and a relative humidity of (45–50) % in order to standardize water absorption. The prepared samples were placed in plastic cups with a diameter of 40 mm, filling them to a height of 30 mm. Then, the samples were compressed twice to 50% deformation at a speed of 2 mm/s; the interval between the first and second compression was 5 s. The load during the test was 15 g. The TPA (texture profile analysis) method is a double compression test (“two bite test”) that simulates the chewing process [10, 28]. The following textural parameters were determined during the analysis:

- hardness (H, g) – maximum force value recorded during the first compression;
- plasticity (P, %) – ratio of the degree of recovery of the sample to its initial height;
- elasticity (E, g) – product of hardness and cohesiveness;
- chewing ability (CA, %) – product of hardness, cohesiveness, and elasticity.

Each measurement was performed in five repetitions. The results of TPA are represented in the form of a “force-time” or “force-deformation” curve, according to which the following indicators are additionally determined:

- hardness ($F1$, g) – maximum force of the first peak;

– adhesiveness ($A3, g \times s$) – area of the negative section of the curve. Cohesion ($A2 / A1$) – ratio of the areas under the second and first peaks;

– plasticity ($A5 / A4$) – ratio of the corresponding sections characterizing the restoration of the structure;

– elasticity ($T2 / T1$) – ratio of the time of formation of the second and first peaks;

– chewing ability (CA) – an integral indicator calculated as $F1 \times (A2 / A1) \times P$.

This approach provides a comprehensive assessment of the mechanical and structural properties of the test samples [10, 28].

Statistical analysis. To process the results of a series of parallel measurements (at least three repetitions), one-way analysis of variance (ANOVA) was used. The data obtained are represented in tables as mean \pm standard deviation ($M \pm SD$). Differences were considered statistically significant at a significance level of $p \leq 0.05$. Tukey's multiple comparison criterion (Tukey's HSD) was used to establish significant differences between mean values. Basic statistical processing and one-way analysis of variance were performed using the Minitab statistical software package, version 18.1 (Minitab Inc., USA) [9].

5. Results of studies on the influence of the food additive "Laminaria + NPFe₃O₄" on the quality indicators of beef steaks

5.1. Studying the influence of the food additive "Laminaria + NPFe₃O₄" on the sensory properties of experimental samples of steaks by the flavor profile method

The flavor profile method is one of the group of methods used to describe sensory characteristics and is considered fundamental for many other descriptive methods. This method is recommended for use in the development and modification of food products (ASTM E253-24: Standard Terminology Relating to Sensory Evaluation of Materials and Products) [28, 29]. The concept of "flavor" is understood as a complex sensation in the oral cavity, caused by the taste, smell, and texture of a food product.

The flavor profile method is an attempt to characterize "flavor", taking into account all the descriptors that form the overall impression of the product. When using this method, the advantages of tasting analysis over instrumental analysis are particularly noticeable since only a person is able not only to perceive a set of organoleptic properties within one dimension but also to analyze them. In essence, flavor was evaluated using a set of descriptors, taking into account their nature, intensity, order of manifestation, aftertaste, and completeness, which determines the overall impression of the product [28, 29].

Based on previous studies of consumer preferences, a set of 10 descriptors was defined to characterize flavor. In addition, for the profile analysis, a conditional reference sensory profile of high-quality beef steak was used as a standard, formed by an expert tasting board on the basis of regulatory requirements and a set of desired organoleptic characteristics: harmonious and characteristic meat taste and aroma, juicy and plastic consistency, absence of excessive density and foreign flavors. The control (sample 1)

was a steak without the addition of NFACC "Laminaria + NPFe₃O₄", and experimental samples 2, 3, and 4 contained 0.1%, 0.2%, and 0.3% of the additive, respectively (Table 1).

Table 1

Sensory evaluation of beef steaks using the flavor profile method, $p \leq 0.05$

Descriptors	Intensity of characteristics, score				
	Beef steak test samples				
	Reference	Sample 1 – control	Sample 2	Sample 3	Sample 4
Aroma and taste characteristics					
Harmonious	5.0	4.0 \pm 0.10	4.5 \pm 0.10	5.0 \pm 0.10	4.8 \pm 0.10
Proper	4.5	3.0 \pm 0.01	4.0 \pm 0.01	4.5 \pm 0.01	4.4 \pm 0.01
Meaty	4.5	4.5 \pm 0.10	4.5 \pm 0.10	4.5 \pm 0.10	4.5 \pm 0.10
Weakly pronounced	3.5	3.0 \pm 0.02	2.5 \pm 0.02	2.0 \pm 0.02	2.2 \pm 0.02
Salty	3.0	3.0 \pm 0.01	2.8 \pm 0.01	2.5 \pm 0.01	2.5 \pm 0.01
Salty-marine	3.0	–	2.8 \pm 0.01	3.0 \pm 0.01	3.0 \pm 0.01
Consistency characteristics					
Juicy	3.0	2.0 \pm 0.20	2.7 \pm 0.10	3.0 \pm 0.10	3.0 \pm 0.10
Plastic	3.5	3.0 \pm 0.10	2.8 \pm 0.10	3.5 \pm 0.10	3.0 \pm 0.10
Dense	1.5	2.0 \pm 0.02	2.5 \pm 0.02	3.0 \pm 0.02	3.2 \pm 0.02
Overall impression	5.0	4.5 \pm 0.10	4.8 \pm 0.20	5.0 \pm 0.20	4.8 \pm 0.20
Sum of points	36.5	27.0 \pm 0.40	34.2 \pm 0.40	37.0 \pm 0.40	36.1 \pm 0.40

As a result of our experimental studies (Table 1), it was found that the addition of NFACC "Laminaria + NPFe₃O₄" in an amount of 0.1%; 0.2%; and 0.3% improves the taste, aroma, and textural characteristics of steaks, providing a more harmonious taste, a pleasant salty-sea hue, and a delicate plastic consistency. The overall organoleptic assessment confirms the advantages of using NFACC "Laminaria + NPFe₃O₄": the highest sum of points was received by sample 3 (37.0 points), which exceeds the standard (36.5 points) and other experimental samples. The excess of the total score of the standard by sample 3 is explained by the appearance of an additional positive descriptor – a light salty-sea hue of taste and aroma, characteristic of kelp components, which was positively perceived by tasters and increased the overall sensory impression of the product. That is, the standard should be considered as a reference guideline, and not as an absolute limit value that cannot be exceeded. Sample 4 is also characterized by high quality (36.1 points), while sample 2 has slightly lower indicators (34.2 points), and the control has the lowest (27.0 points). Thus, the best sensory indicators were obtained for the sample with 0.2% NFACC "Laminaria + NPFe₃O₄" (sample 3), which demonstrated the highest overall organoleptic assessment and the greatest approximation to the standard characteristics.

For visual perception of the results, a detailed flavor profile of the experimental steak samples was constructed (Fig. 2).

It is the profile analysis (Fig. 2) that makes it possible to reveal the intensity of positive and negative characteristics of taste and aroma that makes one test sample (control sample 1) different from the others (samples 2–4). Thus, using the profile analysis, a more objective assessment of the organoleptic indicators of beef steaks fortified with a nanostructured food additive of combined composition (NFACC "Laminaria + NPFe₃O₄").

Additionally, the rational concentration of the food additive "Laminaria + NPFe₃O₄", which is 0.2% of the mass of the recipe mixture, was justified.

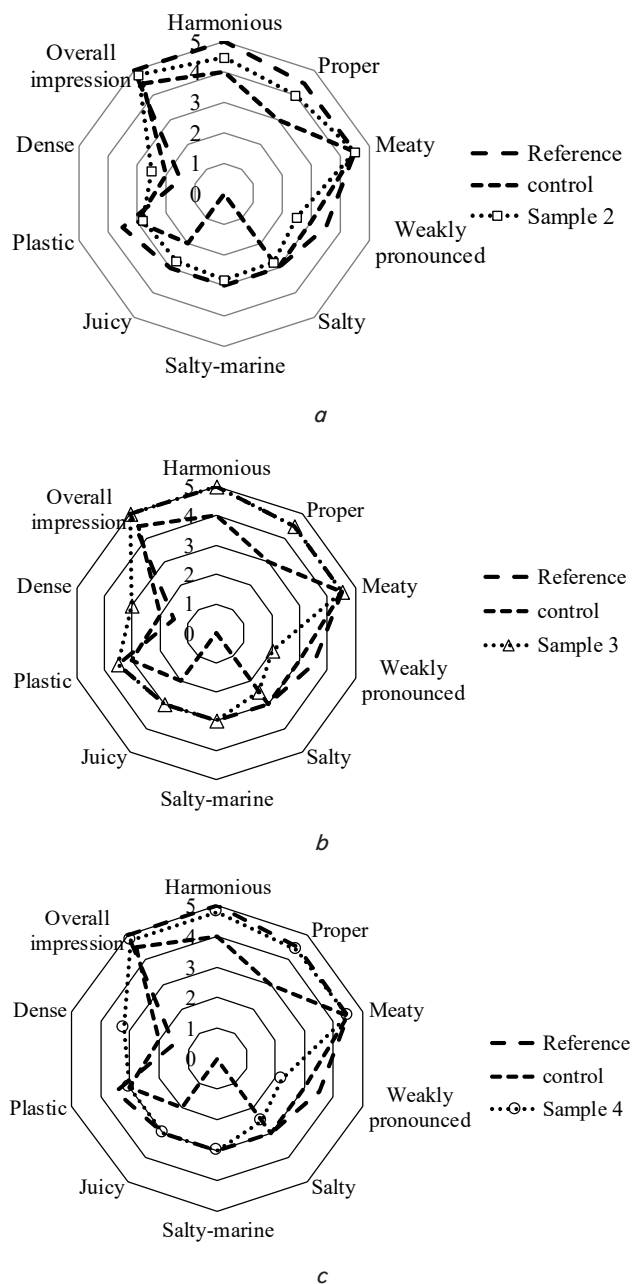


Fig. 2. Profilograms of experimental samples of beef steaks fortified with the “Laminaria + NPF₃O₄” food additive: *a* – reference, control sample 1, sample 2 with 0.1% additive; *b* – reference, control sample 1, sample 3 with 0.2% additive; *c* – reference, control sample 1, sample 4 with 0.3% additive

5.2. Studying the influence of the food additive “Laminaria + NPF₃O₄” on the color characteristics of experimental samples of beef steaks

The appearance of food products is one of the most important criteria for assessing their quality, especially in the case of meat products. The color of meat is formed under the influence of a number of factors, among which the main role is played by the content of myoglobin (Mb), the age of the animal, the pH level, the type of muscle tissue, and the degree of freshness of the product. With increasing pH, meat, as a rule, acquires a darker color due to changes in its moisture-holding capacity. Thus, fresh beef is characterized by a dark red color,

veal has a pale pink or pinkish-brown hue, while frozen meat is characterized by a duller color [30, 31].

Myoglobin (Mb) is a heme-containing protein that, even after the animal is slaughtered, continues to undergo chemical transformations in the sarcoplasm of muscle fibers. Its concentration and redox characteristics largely determine the color of meat. These processes are influenced by both internal (endogenous) and external (exogenous) factors. In particular, in the presence of oxygen, bright red oxymyoglobin is formed, while limited access to oxygen causes the product to darken. The addition of certain ingredients, in particular nitrites, ensures the appearance of a characteristic pink color, and heat treatment, in the absence of color-fixing substances, leads to a transition of color to a gray-brown spectrum [28, 30–32].

During the heat treatment of fresh, uncured meat, myoglobin denatures, which is accompanied by the formation of a characteristic dull brown color of the interior of the product. At the same time, the final color of the finished meat product depends on the degree of its culinary readiness. Since consumers traditionally perceive the change in color from red in the raw state to brown after cooking as a sign of heat treatment, the internal color of a meat product is often used as an indicator of its readiness and safety [28, 32]. In finished meat products, a gray-brown shade of the interior is usually considered as evidence of sufficient heat treatment, while a pink color is often associated with an insufficient degree of readiness and may raise doubts about the safety of the product [31, 32]. Deviations from the typical color can negatively affect consumers’ perception of the quality and safety of meat products. Thus, color after heat treatment is not only an important organoleptic indicator but also one of the criteria for assessing the safety of finished products [28, 32].

The dark brown color of thermally processed meat is due to the denaturation of myoglobin, a water-soluble heme protein of the sarcoplasm, which is responsible for the red color of raw meat. In this regard, the mechanisms of color formation in thermally processed products differ significantly from the processes characteristic of fresh meat, where myoglobin is in the native state. At the same time, there is a close relationship between the chemical processes in raw and processed meat, and their course is influenced by a wide range of internal and external factors [31, 32].

The thermal stability of myoglobin is determined by a combination of endogenous and exogenous factors that affect its redox properties in fresh meat and the features of changes during heating. The main factors include the pH level, the redox state of the protein, its primary structure (amino acid sequence), as well as the presence of antioxidants and prooxidants. The combined effect of these factors largely determines the specificity of the color formation of finished meat products [32].

Therefore, a deep understanding of the chemical and biochemical characteristics of myoglobin, as well as the mechanisms of meat color formation, is important for devising modern technologies for the production of meat products. This creates prerequisites for extending the shelf life of meat products and ensuring high consumer characteristics of meat products.

Analysis of the color characteristics of experimental samples of beef steaks (Table 2) reveals that the introduction into the recipe of a nanostructured food additive of combined composition – NFACC “Laminaria + NPF₃O₄” (greenish-brown color – Fig. 1) in an amount of 0.1%; 0.2%; and

0.3% of the mass of the recipe mixture (compared to the control) reduces the level of illumination, L^* by (1.02–1.06) times, which indicates a gradual darkening of the samples (due to the presence of two groups of components – mineral (Fe_3O_4 NPs) and natural pigments of the brown macroalga *Laminaria* (*Laminaria* sp.).

The results of our study showed (Table 2) that the addition of NFACC “*Laminaria* + NPF_3O_4 ” significantly changes the color parameters of beef steaks, contributing to the formation of more pronounced yellow-brown shades, while the most balanced color indicators were observed with the addition of 0.2% of the additive. Specifically, the a^* parameter showed a slight increase at the concentration of NFACC “*Laminaria* + NPF_3O_4 ” – 0.1% (sample 2). Further, a significant decrease is observed at higher levels of NFACC concentration of “*Laminaria* + NPF_3O_4 ” – 0.2% and 0.3% (sample 3 and sample 4, respectively). This reflects a decrease in redness due to the influence of green-brown pigments of NFACC. On the contrary, the b^* and H^* values increased significantly – by (1.16–1.42) times and (1.08–1.43) times, respectively, indicating a shift towards yellow-brown shades (associated with the addition of Fe_3O_4 NP and *Laminaria* pigments). The chromaticity (C^*) reached its maximum at 0.2% NFACC (sample 3), indicating optimal color saturation, while ΔE^* increased with the content of NFACC “*Laminaria* + NPF_3O_4 ”, with the largest deviation observed in sample 4.

coxanthin provides yellow-brown shades, and Fe_3O_4 NPs enhance the color saturation of the system. The combined effect of these factors forms a characteristic dark brown with an olive tint color of the minced meat product – beef steak, fortified with NFACC “*Laminaria* + NPF_3O_4 ”.

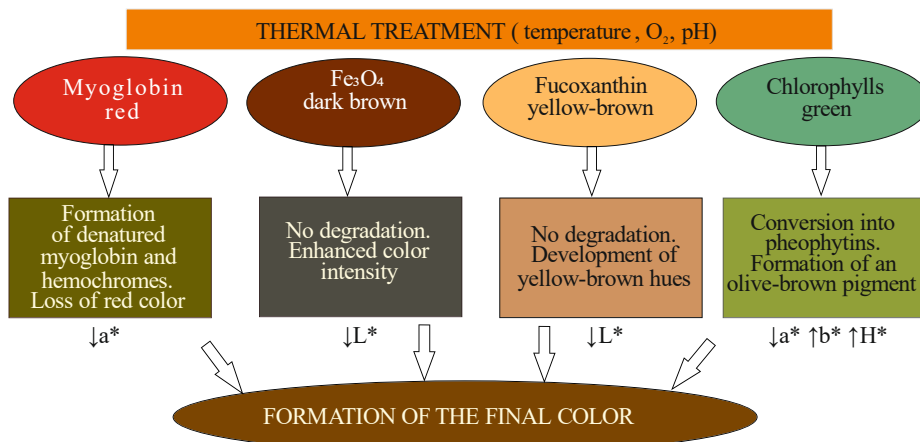


Fig. 3. Scheme of transformation of pigments in beef steaks fortified with the food additive “*Laminaria* + NPF_3O_4 ” during heat treatment

5. 3. Studying the influence of the food additive “*Laminaria* + NPF_3O_4 ” on the structural and mechanical properties of experimental samples of beef steaks by the method of texture profile analysis (TPA)

The texture of chopped meat products – beef steaks – is an important factor of consumer acceptability, in addition to appearance and taste. The texture of a chopped meat product is inextricably linked to its structure at the micro- and macro-levels. Its formation is influenced by food biopolymers, vitamin-mineral complex, biologically active compounds, as well as water and fat content. In particular, researchers

Table 2

Color characteristics of experimental samples of beef steaks, $p \leq 0.05$

Experimental 1samples	L^*	a^*	b^*	ΔE	H^*	C^*
Control – sample 1	58.5 ± 0.3^a	12.8 ± 0.3^a	10.2 ± 0.2^d	–	38.5 ± 0.2^d	16.4 ± 0.1^c
Sample 2 – with 0.1% NFACC	57.2 ± 0.3^b	13.2 ± 0.4^a	11.8 ± 0.3^c	4.2 ± 0.3^c	41.6 ± 0.2^c	17.7 ± 0.1^{ab}
Sample 3 – with 0.2% NFACC	56.0 ± 0.3^c	11.5 ± 0.3^b	13.6 ± 0.4^b	8.1 ± 0.3^b	49.4 ± 0.2^b	17.8 ± 0.1^a
Sample 4 – with 0.3% NFACC	55.0 ± 0.4^d	9.8 ± 0.2^c	14.5 ± 0.4^a	11.6 ± 0.3^a	55.3 ± 0.2^a	17.5 ± 0.1^b

Note: ^{a-c} means in the same column with different superscripts are significantly different when $p < 0.05$.

The formation of the color of food systems, in particular beef steaks fortified with Fe_3O_4 nanoparticles and components of the brown macroalga *Laminaria* (*Laminaria* sp.), is determined by the combined transformation of meat and plant pigments during heat treatment under the influence of temperature, oxygen, and changes in the pH of the medium. Fig. 3 shows a scheme of the transformation of pigments in beef steaks fortified with NFACC “*Laminaria* + NPF_3O_4 ” during heat treatment.

From the analysis of Fig. 3 it follows that during heat treatment a complex transformation of pigments occurs: denaturation of myoglobin leads to the formation of gray-brown hemichromes, while chlorophylls of *Laminaria* are converted into pheophytins with an olive-brown color. Fu-

show that textural differences were detected as a result of differences in the microstructure of minced meat, in which soy protein isolate created a more compact structure than extrudates made from pea protein isolate [28, 33]. When comparing the texture profile with the structural characteristics of minced meat products, a similar trend can be observed for products fortified with soy protein isolate. Based on micrographs, such products showed a compact structure, which leads to a harder and more elastic texture [28]. However, microstructure is only one of the factors affecting product hardness. It has been shown in numerous works that the presence of components such as starch, methylcellulose and dietary fiber in different concentrations affects the texture of minced meat [28, 33, 34]. In addition, the components of the meat product must be palatable, must be released from the food matrix in order to reach the corresponding taste receptors. This flavor release is closely related to the way the food structure is broken down in the mouth, which concerns both the initial texture of the food product and the change in texture during chewing. Table 3 and Fig. 4 illustrate an analysis of the structure profile of experimental samples of beef steaks fortified with NFACC “*Laminaria* + NPF_3O_4 ”.

Table 3

Results from texture profile analysis (TPA) of beef steak samples, $p \leq 0.05$

Experimental samples	Hardness, g	Plasticity, g	Elasticity, g	Chewing, %
Control – sample 1	83.8 ± 0.1 ^a	52.2 ± 0.1 ^a	46.6 ± 0.1 ^a	74.26 ± 0.01 ^a
Sample 2 – with 0.1% NFACC	86.9 ± 0.1 ^b	60.3 ± 0.1 ^b	47.3 ± 0.1 ^b	76.12 ± 0.01 ^{ba}
Sample 3 – with 0.2% NFACC	87.4 ± 0.1 ^{cb}	64.1 ± 0.1 ^c	48.2 ± 0.1 ^c	76.90 ± 0.01 ^{cb}
Sample 4 – with 0.3% NFACC	88.1 ± 0.1 ^{dc}	66.0 ± 0.1 ^d	48.9 ± 0.1 ^{dc}	76.99 ± 0.01 ^{dc}

Note: ^{a-c} means in the same column with different superscripts are significantly different when $p < 0.05$.

Analysis of experimental data (Table 3, Fig. 4) reveals a clear trend in the change of textural indicators depending on the concentration of the nanostructured food additive of combined composition – NFACC “Laminaria + NPFe₃O₄”.

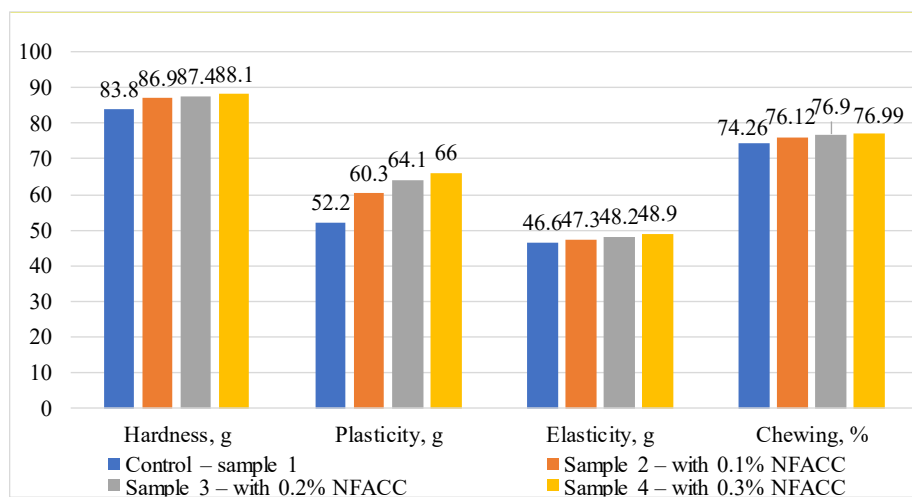


Fig. 4. Texture profile of steak samples

With an increase in the content of NFACC, the textural indicators change, specifically the hardness of the samples gradually increases (from 83.8 g in the control to 88.1 g in sample 4 – at 0.3% of the food additive). The plasticity (stability) indicator increases (from 52.2% to 66.0%). Elasticity also increases (from 46.6 g to 48.9 g). The chewing ability (chewing) indicator increases (from 74.26% to 76.99%). That is, the addition of NFACC “Laminaria + NPFe₃O₄” positively affects the textural properties of beef steaks by increasing moisture retention capacity, gelation, and structure formation. The optimal concentration is 0.2% by weight of the recipe mixture, which provides the best balance between tenderness, plasticity, and chewing ability of the minced meat product.

6. Discussion of results based on investigating the influence of the food additive “Laminaria + NPFe₃O₄” on the quality of beef steaks

Improvement of the sensory profile of experimental samples of steaks fortified with a nanostructured food additive of the combined composition NFACC “Laminaria + NPFe₃O₄” is associated with the synergistic effect of the additive components: kelp components and Fe₃O₄ nanoparticles. Fe₃O₄ NPs are characterized by a high specific surface area and the ability to interact with protein components of the meat system. This contributes to strengthening the spatial structure of minced meat, increasing the density of products, and stabilizing the structure of the finished product. In addition, the uniform distribution of nanoparticles in the system en-

ures uniformity of consistency without the appearance of foreign flavors and odors [1, 9, 10]. Laminaria polysaccharides, in particular alginates, increase the moisture-holding capacity of minced meat, which provides greater juiciness, plasticity, and uniformity of consistency. Laminaria algae also contains natural flavorings that form a pleasant salty-marine shade and harmonize the overall flavor of the product. This is confirmed in studies by many researchers [1, 3, 15, 18, 19, 23–27].

As a result of sensory evaluation using the flavor profile method (Table 1), it was found that the highest level of taste harmony (5.0 points) was achieved in sample 3 (0.2% NFACC “Laminaria + NPFe₃O₄”), while samples 2 and 4 had slightly lower values (4.5 and 4.8 points, respectively), and control sample 1 had the lowest indicator (4.0 points). A similar trend is observed for the descriptor “inherent taste”: the maximum values are characteristic of samples 3 and 4 (4.5 and 4.4 points, respectively), while the control was characterized by a significantly lower intensity (3.0 points) and a strong meaty aftertaste. The meaty taste in all test samples remained stably pronounced (4.5 points), which indicates the preservation of the traditional organoleptic properties of the product when adding NFACC “Laminaria + NPFe₃O₄”. At the same time, the intensity of the weakly expressed aftertaste in the experimental samples (2–4) is lower than the standard, which indicates an improvement in the taste profile.

According to the aromatic characteristics, the experimental samples (2–4) were distinguished by a more balanced profile compared to the control. They received the highest scores; no negative aroma components, foreign and pungent odors were detected, which confirms the positive effect of the food additive. And the introduction of NFACC “Laminaria + NPFe₃O₄” contributed to the formation of a pleasant salty-marine shade (2.8–3.0 points), which was absent in the control sample.

Consistency indicators also improved with increasing dosage of NFACC “Laminaria + NPFe₃O₄”. The highest values of juiciness and plasticity are characteristic of sample 3 (3.0 and 3.5 points, respectively), which corresponds to the reference values. The control sample was characterized by lower juiciness (2.0 points) and less pronounced structural uniformity. The density of the product increased with increasing content of the food additive, reaching maximum values in sample 4.

By means of profile analysis, it was determined – due to what intensity of positive and presence of negative character-

istics of taste and aroma one test sample (control sample 1) differs from others (samples 2–4). That is, a more objective assessment of the organoleptic indicators of beef steaks fortified with a nanostructured food additive of combined composition (NFACC “Laminaria + NPFe₃O₄”). Beef steaks (control sample 1) were characterized by a gray color, a salty taste, and a plastic, dense consistency throughout the mass, which indicates the need to adjust their recipe to maximally approach the standard (Fig. 2).

As a result of organoleptic studies, it was established that it is appropriate to introduce the NFACC “Laminaria + NPFe₃O₄” into the recipe of beef steaks, which provides a harmonious salty-sea taste, a delicate plastic consistency, and a dense structure on the cut. A comparison of the overall score showed that sample 3 with the addition of 0.2% NFACC “Laminaria + NPFe₃O₄” is closest to the standard. The optimal concentration of NFACC “Laminaria + NPFe₃O₄” (0.2%) provides a harmonious combination of taste, aroma, and consistency, while a further increase in dosage increases the density of the product without a significant improvement in organoleptic indicators. The obtained changes in the color characteristics of steaks are explained by the synergistic effect of Fe₃O₄ nanoparticles and *Laminaria sp.* pigments. Fe₃O₄ nanoparticles cause darkening of the product and a decrease in brightness [1, 8–10], while fucoxanthin, carotenoids, and phaeophytins of kelp form yellow-brown and olive shades [1, 3, 4, 18]. As a result, the color of the meat product shifts towards the brown-olive spectrum, increasing yellowness and overall color difference [10, 18, 28]. A number of works have proven a significant change in the natural color of food products when using algae (such as spirulina, chlorella, kelp, or wakame) [1, 9, 28].

A feature of the proposed approach is the use of a nanostructured food additive of the combined composition – NFACC “Laminaria + NPFe₃O₄”, which combines the functional properties of biologically active components of kelp and Fe₃O₄ nanoparticles. In contrast to studies that used only seaweed or its extracts [15, 18, 19, 23–27], our work established a synergistic effect of the additive components on the formation of taste, aroma, and consistency of steaks. Our results confirm the improvement of juiciness, plasticity, structural uniformity, and harmony of taste at an optimal concentration of 0.2% of the NFACC “Laminaria + NPFe₃O₄”.

Analysis of the color characteristics of experimental samples of beef steaks revealed (Table 2) that the introduction of NFACC “Laminaria + NPFe₃O₄” significantly affects the color characteristics of finished meat minced products, causing a shift in color towards more saturated yellow-brown shades. At the same time, the optimal color balance was achieved at a concentration of 0.2% NFACC “Laminaria + NPFe₃O₄” (sample 3). The dark color in the composition of NFACC is formed due to two groups of components – mineral (iron oxide) and natural pigments of brown algae *Laminaria sp.* Iron oxide (Fe₃O₄) is characterized by a mixed valence state Fe²⁺/Fe³⁺. This determines its intense optical properties and wide light absorption. This determines the dark brown color of nanoparticles (Fe₃O₄ NPs), and in food systems, their ability to cause darkening (decrease in L^*) and affect the redox processes of pigments, in particular myoglobin [8, 9, 10].

The pigment complex of *Laminaria sp.* is represented by fucoxanthin, chlorophylls (a, c), their degradation products (phaeophytins), and other carotenoids, which causes characteristic color changes in food systems [1, 3, 4, 18, 19, 28]. Fucoxanthin is the main carotenoid of brown algae and

is characterized by a yellow-brown or olive color, which contributes to the formation of a brown-olive shade of the product, an increase in the yellowness index (b^*) and a shift in the color tone towards the yellow-brown spectrum (increased H^*) [4, 18, 28]. Chlorophylls (a and c) give a green color but, in combination with carotenoids, they form greenish-brown shades. During heat treatment and under conditions of decreasing pH, chlorophylls degrade to form pheophytins, which have an olive-brown color, causing the product to darken and reduce the brightness of the color. Pheophytins play an important role in the formation of darker, muted shades, which is accompanied by a decrease in lightness ($\downarrow L^*$) and chromaticity ($\downarrow C^*$) [4, 18, 28]. Other carotenoids (in particular β -carotene) are characterized by a yellow-orange color and additionally enhance the yellowness (increased b^*) and color saturation (increased C^*) [4, 18, 28]. Thus, the combined effect of *Laminaria sp.* pigments causes a shift in the color characteristics of food systems towards the yellow-brown and olive spectrum with a decrease in lightness and the formation of darker and less bright tones.

As a result of the synergistic interaction of both components of NFACC, a more intense color of the product is formed (L^* is significantly reduced). At the same time, a color shift occurs to brown-olive and gray-brown shades ($\downarrow a^*$, $\uparrow b^*$, $\uparrow H^*$) and a modification of the color saturation ($\uparrow C^*$) to the optimal level at a concentration of the food additive of 0.2%; with a gradual increase in the total color difference ($\uparrow \Delta E^*$). Our results confirm that 0.2% of NFACC provides the most balanced color characteristics of beef steaks, namely the most attractive, natural color, balance between saturation and typicality for a meat product, absence of excessive darkening, as in sample 4.

The results of our analysis of the color change of experimental samples of steaks fortified with NFACC “Laminaria + NPFe₃O₄” during heat treatment (Fig. 3) are explained by the complex transformation of meat and plant pigments at high temperatures. The process is also carried out under the influence of oxygen and changes in the acidity of the environment (pH). Denaturation of myoglobin is accompanied by the formation of gray-brown hemichromes and a decrease in redness, kelp chlorophylls are converted into olive-brown pheophytins, and thermostable fucoxanthin preserves and enhances yellow-brown shades. This mechanism of color transformations of meat and vegetable pigments has been proposed in [18, 30–33]. Fe₃O₄ nanoparticles remain stable and enhance the darkening of the product [8–10]. The combined effect of these processes ensures the formation of a characteristic dark brown color with an olive tint, a decrease in lightness and redness, and an increase in yellowness and color saturation.

At the initial stage, the color of the system is formed by the combination of myoglobin (red), Fe₃O₄ nanoparticles (dark brown), fucoxanthin (yellow brown), and chlorophylls (green). During heating, myoglobin denatures with its transition to metmyoglobin and hemichromes, which is accompanied by the loss of red color and the formation of gray-brown tones ($\downarrow a^*$). Fe₃O₄ NPs remain thermally stable and, due to intense light absorption, enhance the dark background of the product, causing a decrease in the level of illumination ($\downarrow L^*$) and general darkening of the system. Chlorophylls, under conditions of heating and lowering pH, lose the Mg²⁺ ion and transform into pheophytins, which have an olive-brown color. This process is crucial for the formation of greenish-brown shades and is accompanied by a shift in the color tone to the yellow-olive region ($\uparrow H^*$), a decrease in the a^* index, as well as a partial increase in the b^* index.

Fucoxanthin, as the main carotenoid of brown algae, is characterized by relative thermal stability, undergoing partial isomerization and oxidation with the formation of stable yellow-brown compounds. This ensures the preservation or enhancement of yellowness ($\uparrow b^*$) and an increase in color saturation ($\uparrow C^*$). As a result of the combined action of these processes, an integral color is formed, combining gray-brown (denatured myoglobin), dark (Fe_3O_4), olive-brown (pheophytins) and yellow-brown (fucoxanthin) components. This causes the formation of a dark brown or olive-brown shade of the minced meat product. From the standpoint of the CIELab colorimetric system, such changes are characterized by a decrease in lightness ($\downarrow L^*$) under the influence of Fe_3O_4 , a decrease in redness ($\downarrow a^*$) due to myoglobin denaturation, an increase in yellowness ($\uparrow b^*$) and saturation ($\uparrow C^*$). This is explained by the content of carotenoids, as well as the shift of the color tone ($\uparrow H^*$) to the yellow-olive region due to the formation of pheophytins. The combined effect is manifested in the increase in the total color difference (ΔE^*), which reflects a significant transformation of the original color of the food matrix. This agrees with the statements from other specialists [30–32].

Thus, during the heat treatment, complex transformations of the pigment system occur; denaturation of myoglobin is accompanied by the formation of gray-brown hemichromes, while chlorophylls of *Laminaria sp.* are transformed into pheophytins with a characteristic olive-brown color. Fucoxanthin contributes to the formation of yellow-brown shades, and Fe_3O_4 nanoparticles enhance the intensity and saturation of the color. The combined effect of these processes ensures the formation of a characteristic dark brown color of the finished minced meat product with an olive shade.

Therefore, the combined use of Fe_3O_4 NPs and *Laminaria sp.* pigments allows for targeted regulation of the color characteristics of beef steaks, forming a darker, richer, and more stable color, which can be considered as a functional and technological tool for controlling the appearance of minced meat products.

A feature of the proposed approach is a comprehensive analysis of the color characteristics of steaks fortified with NFACC “*Laminaria* + NPFe_3O_4 ” before and after heat treatment using the parameters of the CIELab system (L^* , a^* , b^* , C^* , H^* , ΔE^*). Unlike known studies that consider the effect of Fe_3O_4 nanoparticles or brown algae pigments separately on the color of food systems [8, 9, 10, 18, 28], our work investigated their synergistic effect in minced meat products.

It was found that NFACC “*Laminaria* + NPFe_3O_4 ” causes a decrease in lightness (L^*), a decrease in redness (a^*), an increase in yellowness (b^*), a shift in color tone to the yellow-olive region (H^*) and an increase in the total color difference (ΔE^*). Our results are consistent with data on the darkening of food systems under the influence of Fe_3O_4 [8–10] and color changes under the influence of fucoxanthin and chlorophyll degradation products of *Laminaria sp.* [18, 28, 30–33].

In contrast to the literature, which mainly describes separate mechanisms of transformation of meat or plant pigments [30–33], our work proposes a generalized scheme of their joint transformation during heat treatment. It is shown that the denaturation of myoglobin with the formation of hemichromes, the transition of chlorophylls to pheophytins, the preservation of thermostable fucoxanthin and the stability of Fe_3O_4 nanoparticles ensure the formation of a characteristic dark brown color with an olive tint. It was also established that the optimal color characteristics are provided by the introduction of 0.2% of NFACC, which makes it possible to obtain the

most natural and attractive color without excessive darkening of the product. Analysis of the structural and mechanical properties of experimental samples of beef steaks by the TPA method (Table 3, Fig. 4) reveals a pronounced pattern of changes in textural characteristics depending on the level of introduction of the nanostructured food additive of combined composition (NFACC). It was found that with the increase in the concentration of NFACC, a gradual increase in the hardness of the experimental samples is observed: from 83.8 g in the control variant to 88.1 g in sample 4 with the introduction of 0.3% of the food additive. That is associated, firstly with the structure-forming effect of Fe_3O_4 NPs (iron oxide nanoparticles are active centers of interaction with meat proteins, contributing to the compaction of the protein matrix and the formation of a stronger framework) [35]; secondly, with the gel-forming effect of *Laminaria* polysaccharides (alginates and other *Laminaria sp.* hydrocolloids are capable of forming gel-like structures, which at a certain concentration (especially $\geq 0.2\%$) increase the density of the system, which leads to an increase in deformation resistance) [1, 4, 21, 30]. Third: with a decrease in free moisture (binding of water by Fe_3O_4 NPs and *Laminaria* polysaccharides converts H_2O into a bound state, which increases hardness [1, 10]. Fourth: with the formation of a combined protein-polysaccharide network (synergy between meat proteins, *Laminaria* polysaccharides, and Fe_3O_4 NPs forms a more compact and strong structure). This is in agreement with the findings by other researchers [18, 19, 28, 30]. However, the concentration of NFACC “*Laminaria* + NPFe_3O_4 ” was not sufficient to achieve an undesirable statement according to Regulation (EC) No. 1924/2006 of the European Parliament and of the Council.

The plasticity (stability) index increases (from 52.2% to 66.0%), which indicates a better ability of the product to restore its shape after deformation. This is due to the gel-forming properties of *Laminaria* alginates and the structure-forming effect of Fe_3O_4 NPs, which act as binding centers in the protein-polysaccharide system. Namely: strengthening and stabilizing the product structure through electrostatic intermolecular interactions of biopolymer ingredients: hydrophobic and polar regions of macromolecules, ionogenic and ionized groups, etc.

The elasticity also increases (from 46.6 g to 48.9 g), which indicates a strengthening of the internal bonds of the structure. This is the result of: synergistic interaction of meat proteins with *Laminaria* polysaccharides; uniform distribution of moisture and stabilization of the structure under the influence of Fe_3O_4 NPs.

The chewability index (chewing ability) increases (from 74.26% to 76.99%), which indicates an improvement in the textural appeal of the product. Chewing ability directly depends on hardness ($\text{CA} = \text{hardness} \times \text{cohesiveness} \times \text{plasticity}$), so its increase is natural. The product requires more effort to chew but, at the same time, can be perceived as “meatier” and more structured.

Thus, the sample with 0.2% NFACC “*Laminaria* + NPFe_3O_4 ” demonstrates the most balanced combination of textural characteristics: a slight increase in hardness, which is accompanied by an increase in elasticity and plasticity. This contributes to the formation of a more compact and strong structure, but at the same time elastic and integral; a significant increase in elasticity and plasticity; the optimal value of chewing ability. Further increase in concentration to 0.3% does not provide a significant improvement in the indicators, therefore it is not advisable. In addition, at the maximum concentration (0.3%), excessive compaction of the structure is possible, which can reduce the sensory ten-

derness of the product, even despite the high values of other textural indicators. That is why the NFACC concentration of 0.2% can be considered an optimal compromise between hardness and consumer acceptability.

A feature of our results is the comprehensive assessment of the textural characteristics of steaks fortified with NFACC “Laminaria + NPFe₃O₄” by the TPA (Texture Profile Analysis) method, which allowed us to simultaneously determine the hardness, plasticity, elasticity, and chewiness of the product. Unlike known studies that consider separately the effect of *Laminaria sp.* polysaccharides or Fe₃O₄ nanoparticles on the structure of food systems [18, 19, 28, 30, 35], our work has investigated their synergistic effect in minced meat products.

It was found that the introduction of NFACC contributes to the formation of a denser protein-polysaccharide matrix, increasing hardness, plasticity, elasticity, and chewing ability. Our results are consistent with the literature data on the structure-forming role of brown algae alginates and iron oxide nanoparticles [18, 19, 28, 30], but their feature is the complex (synergistic) nature of the action of the additive components, which provides a combined effect on the texture of beef steaks.

Thus, the feasibility of using 0.2% NFACC “Laminaria + NPFe₃O₄” in the technology of beef steaks has been justified by the set of organoleptic, color and structural and mechanical indicators. It has been established that this concentration ensures the formation of a product with high consumer appeal, optimal textural properties, and stable color characteristics and can be recommended for the development of functional meat products of increased biological value.

A feature of our results is also the establishment of regularities in the formation of sensory, color, and structural-mechanical properties of beef steaks using a nanostructured food additive of combined composition “Laminaria + NPFe₃O₄”, which combines components of brown algae *Laminaria sp.* and nanoparticles of iron oxide Fe₃O₄. The synergistic nature of the action of the additive components is shown, which provides a comprehensive effect on the quality characteristics of minced meat products, and its rational concentration at the level of 0.2% of the mass of the recipe mixture is justified.

The scope of practical application of our results includes the technology of production of minced meat products. Expected effects from the implementation of the NFACC “Laminaria + NPFe₃O₄” are improvement of organoleptic and textural characteristics of products and expansion of the range of functional meat products of increased biological value.

A feature of our research is the use of a single combined nanostructured food additive that combines the functional and technological properties of brown algae and iron oxide nanoparticles, while known studies are mainly based on the use of these components separately.

The limitations of the research on sensory, color, and structural and mechanical indicators are that the results were obtained only for beef steaks and within the studied range of additive concentrations. The reproducibility of the established effects requires confirmation for other recipes, types of meat raw materials, and production conditions.

The disadvantage of the study is the lack of instrumental confirmation of the mechanisms of interaction between “Laminaria + NPFe₃O₄” and the minced beef matrix. In the future, this can be eliminated by conducting microstructural, rheological, and spectroscopic studies.

The prospects for further research are associated with an in-depth study of the proposed technology as our results confirm its effectiveness and indicate the feasibility of further

improvement and practical implementation. The obtained experimental data provide grounds to substantiate the prospects of using the NFACC “Laminaria + NPFe₃O₄” in the technologies of various types of minced meat products, in particular, steaks, cutlets, beef tenderloins, rump steaks, meatballs, rolls, and other products with improved quality indicators.

At the same time, to fully determine the functional and technological potential of a nanostructured food additive of combined composition (NFACC), it is necessary to conduct additional mathematical, methodological, and experimental studies. Special attention is required to assess the impact of the innovative ingredient NFACC “Laminaria + NPFe₃O₄” on the functional and technological properties, nutritional value, and quality characteristics of various types of meat products. In addition, the use of Fe₃O₄ nanoparticles in food systems requires a comprehensive assessment of their safety. Despite the use of low concentrations of NFACC and the absence of a negative impact on the quality indicators of steaks, further study on the issues of bioavailability, possible migration, accumulation, and long-term effects of nanoparticles on the human body is required.

Therefore, a promising area is to conduct toxicological, biokinetic, and biomedical studies to scientifically substantiate the safety of using NFACC “Laminaria + NPFe₃O₄” in the technologies of functional meat products.

7. Conclusions

1. We have found that the introduction of NFACC “Laminaria + NPFe₃O₄” in an amount of 0.1–0.3% improves the organoleptic characteristics of beef steaks. The highest overall sensory score was received by the sample with 0.2% NFACC – 37.0 points, which exceeds the standard (36.5 points) and the control sample (27.0 points). At this concentration, a harmonious taste and aroma profile and a delicate plastic consistency of the product were formed.

2. It was found that the introduction of NFACC “Laminaria + NPFe₃O₄” naturally changes the color characteristics of steaks: it reduces the lightness (L^*) by 1.02–1.06 times and increases the yellowness (b^*) by 1.16–1.42 times and the color tone (H^*) by 1.08–1.43 times. The most balanced and attractive color characteristics were obtained at a concentration of 0.2% NFACC, which ensures the formation of a stable dark brown color with an olive tint without excessive darkening of the product.

3. The TPA method established that increasing the concentration of NFACC from 0 to 0.3% increases the hardness of steaks from 83.8 to 88.1 g, plasticity from 52.2 to 66.0%, elasticity from 46.6 to 48.9 g, and chewiness from 74.26 to 76.99%. The optimal balance of textural characteristics was achieved with the addition of 0.2% NFACC, while a further increase in the concentration to 0.3% causes excessive compaction of the structure.

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 and the results reported in this paper.

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Data availability

All data are available 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.

Author contributions

Iryna Tsykhanovska: Conceptualization, Investigation, Data Curation; **Lidiia Tovma:** Investigation, Resources; **Oleh Lytvyn:** Methodology; **Alexandr Alexandrov:** Writing – original draft; **Tatyana Lazareva:** Validation; **Viktoriia Yevlash:** Investigation; **Oleh Lushchenko:** Formal analysis; **Ihor Morozov:** Validation; **Sergiy Kaplun:** Writing – review & editing; **Vasyl Vakuliuk:** Writing – review & editing.

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