# Meat cutlets with iron oxide nanoparticles and alga *Laminaria japonica*

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## Abstract

**Introduction.** The aim of the study was to produce beef cutlets with enhanced biological value using a complex food additive based on iron oxide nanoparticles and dried powder of the brown alga *Laminaria japonica* (kelp).

**Materials and methods.** A complex food additive was incorporated at levels of 0.1, 0.2, and 0.3% by weight into the beef cutlet formulation. Physicochemical, structural-mechanical, functional, and technological properties of the minced beef and the cutlets made from it were evaluated using standard methods.

**Results and discussion.** The complex food additive (CFA) was incorporated into minced beef in powder form during the mixing process. It was found that adding the CFA at a level of 0.2% significantly improved the sensory characteristics of the cutlets compared to the control: appearance (shape) improved by 1.15 times, consistency by 1.18 times, color intensity increased by 6%, and the overall sensory score rose by 17.6%. Simultaneously, the structural and mechanical properties of the minced meat improved: the instantaneous elastic modulus increased by 1.20 times, and the high-elastic modulus by 1.16 times. Functional and technological properties were also enhanced, with water-holding capacity increasing by 1.33 times; water- and fat-binding capacities by 1.30 and 1.27 times, respectively; and fat-holding and fat-emulsifying capacities by 1.29 and 1.27 times, respectively. An improvement in emulsion stability by 1.25 times, along with reduced moisture and fat losses during heat treatment, led to a 5.5% increase in the yield of the final product. The overall digestibility of cutlet proteins increases by 1.12 times, while the acid value decreases by 2.2 times and the peroxide value by 1.6 times. These changes, along with the bacteriostatic properties of the complex food additive, contribute to the stability of the product qualities during storage. The content of protein, starch, dietary fiber, some mineral elements and vitamins increased in the beef cutlets. Based on sensory, structural-mechanical and physicochemical analyses, the optimal concentration of the complex food additive was determined as 0.2% of the total recipe mass. It provides a meat product enriched with iodine to a level of 75±10 mcg per 100 g, which covers more than 50% of the recommended daily allowance for an adult. In addition, it increases the iron content by 27.8% compared to the control sample, which allows it to satisfy more than 10% of the daily requirement for this trace element.

**Conclusions.** A complex food additive based on iron oxide nanoparticles and kelp powder can be used in the formulation of minced meat products to stabilize their structure and improve consumer properties. Due to the presence of valuable nutritional components, it also enhances the biological and nutritional value of beef cutlets.

## Introduction

There has been a growing interest in balanced nutrition and a healthy lifestyle, which has led to an active search for new, healthy food sources, among which seaweed is attracting particular attention. According to the Food and Agriculture Organization (FAO) of the United Nations, approximately 600 species of macroalgae are used in human nutrition worldwide, while in Europe, approximately 200 species have proven food and commercial potential (FAO, 2022; Lähteenmäki-Uutela et al., 2021). The growth of consumer interest in algae has led to the formation of a new concept in the food industry – "phyco-gastronomy" (Milinovic et al., 2021). Among the most popular species in global food production, algae of the genera *Laminaria* and *Saccharina* hold leading positions, accounting for over 34.6% of total production. They are mainly used in the preparation of salads, sauces, and seasonings (Peñalver et al., 2022). In addition to its high nutritional value, seaweed consumption is associated with positive health effects, including reduced blood pressure and prevention of cardiovascular disease (Cotas et al., 2022). In the context of global population growth and increasing scarcity of natural resources, seaweeds are considered a sustainable and promising resource that can enhance food security. They can be grown in seawater, which does not compete with arable land or freshwater resources, making their widespread use possible in both the food industry and aquaculture (Costa et al., 2021, 2024; Farghali et al., 2021).

Improving the nutritional value of meat products is a pressing issue in research and development in food science and nutrition, driven by the need to promote sustainable and efficient protein consumption by the population, as well as the possibility of increasing the biological value of meat products (Maikova et al., 2022; Masliychuk et al., 2024). One promising solution is the addition of non-traditional components to the meat products, in particular seaweeds such as a brown alga *Laminaria* (Choi et al., 2012; Kryzhova et al., 2021; Stabnikova et al., 2025; Vognivenko and Kachur, 2024). Thanks to its rich mineral and amino acid profile, laminaria enhances minced meat products by adding biologically active compounds, improving both their nutritional value and consumer appeal (Alisha and Aisha, 2019; Bondar et al., 2019; Gullón et al., 2019; Moroney et al., 2013; 2015; Tagliapietra and Clerici, 2023).

*Laminaria*, commonly known as kelp, is a rich source of several essential minerals, including iodine, phosphorus, calcium, and iron. It contains up to 1000 μg of organically bound iodine per 100 g of dry matter, which is readily absorbed from seawater. Additionally, it provides approximately 45 mg of phosphorus, 170 mg of calcium, and 3.0 mg of iron per 100 g of dry matter.

The polysaccharides found in algae are characterized by high hydration and adsorption capacities, enabling them to effectively bind and remove toxins from the human body. The sulfated heteropolysaccharide fucoidan acts as a cholesterol antagonist, helping to reduce cholesterol deposits in blood vessels. Additionally, laminaria exhibits anticoagulant properties and has a positive effect on the restoration of digestive system functions as well as on skin health (Costa et al., 2021; Milinovic et al., 2021; Moroney et al., 2013, 2015; Salido et al., 2024).

The inclusion of algae in meat and other food products helps to enrich them with biologically active compounds, in particular proteins, dietary fiber, carbohydrates, vitamins and minerals (Cotas et al., 2024; Stabnikova et al., 2021). The use of algae as food additives imparts functional properties to finished products, including sorption, hydration, radioprotective, antihypertensive, antidiabetic, antioxidant, anti-inflammatory, antitumor, antiviral, antimicrobial activity, as well as the ability to form complexes (Babich et al., 2022; Biancarosa et al., 2018; Cotas et al., 2022; Rogel-Castillo et al., 2023; Salido et al., 2024).

This makes the use of algae as an innovative, non-traditional raw material scientifically and technologically feasible for developing new types of food products, particularly minced meat products. Despite existing studies that have examined the use of edible seaweeds in meat dishes, in particular: laminaria (*Laminaria* sp.), wakame (*Undaria pinnatifida*), nori (*Porphyra umbilicalis*) and sea spaghetti (*Himanthalia elongata*) (Gohara-Beirigo et al., 2021; Cofrades et al., 2017; Peñalver et al., 2020), the specifics of the use of laminaria in meat product technologies, in particular cutlets, are insufficiently covered.

The complex food additive (CFA), consisting of dry kelp biomass powder and iron oxide ($FeO \times Fe_2O_3$) nanoparticles (IONPs), is a finely dispersed powder with a particle size of 0.2 mm, greenish-brown in color, with a characteristic taste and smell of algae (Figure 1) (Tsykhanovska et al., 2024a, 2025).

**Figure 1. Complex food additive**

The aim of the study was to produce beef cutlets with enhanced biological value using a complex food additive based on iron oxide nanoparticles and dried powder of the brown alga *Laminaria japonica.*

## Materials and methods

**Chemicals and raw materials.** All reagents used for the synthesis of $FeO \times Fe_2O_3$ nanoparticles and for the analyses were provided by Merck (Darmstadt, Germany). Food powder of kelp (*Laminaria japonica*) 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). Premium or first grade beef, extra-fine cooking salt (“TM Dr. Igel”, Ukraine), wheat bread (JSC “Kharkiv Bread Factory “Slobozhanskyi””), extra-class Grass-Fed beef rendered fat (“Steaks of the Carpathians”), and 2.5% fat milk (LLC “Agromol”, Ukraine) were purchased at local markets in Kharkiv, Ukraine.

**Preparation of a complex food additive.** Preparation of a complex food additive (CFA) containing dry kelp biomass powder and iron oxide ($FeO \times Fe_2O_3$) nanoparticles is described in detail in (Tsykhanovska et al., 2024a). The CFA contained 15% (w/w) iron oxide nanoparticles (IONPs) and 85% (w/w) laminaria powder and was used as an ingredient in the recipe for beef cutlets.

**Production of beef cutlets.** To prepare the control sample of beef cutlets (designated as BC), a traditional basic recipe was used, consisting of: beef — 74.0 g; wheat bread — 18.0

g; breadcrumbs — 8.0 g; table salt — 1.0 g; cooking fat — 6.0 g; and water or milk — 24.0 g. The total mass of the minced mixture was 125.0 g, yielding 100.0 g of the finished product. In the developed versions of cutlets, a complex food additive (CFA) was added to the recipe in an amount of 0.1, 0.2, and 0.3% (w/w) of the total mass of the mixture. Accordingly, these samples were designated as B1, B2, and B3 (Figure 2).

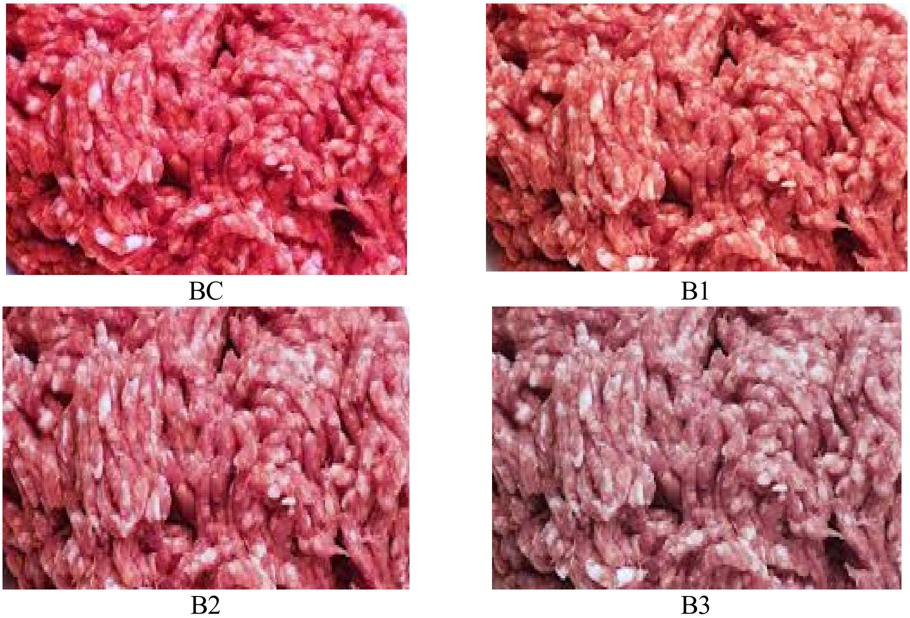

BC
B1
B2
B3

**Figure 2. Minced beef with a complex food additive,% (w/w):**
**0 (BC); 0.1 (B1); 0.2 (B2), and 0.3 (B3)**

Minced meat was obtained by grinding beef and wheat bread swollen in water/milk in an industrial meat grinder MIM-300 Arm-Eco (“Arm-Eco”, Ukraine) followed by mixing with salt, spices and CFA in a meat mixer Farshemis Hendi 282670 (“Hendi”, Netherlands) for 3-5 minutes and keeping the recipe mixture for 8-10 minutes. The minced meat samples were packed in airtight bags and stored at a temperature of (4±1)°C for further physicochemical and structural-mechanical studies.

The heat treatment of the samples 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 cooking, the cutlets were left at room temperature for 2 hours, and then packaged in airtight bags and stored at a temperature of (4±1)°C for further physicochemical analyses and sensory evaluation.

### Minced meat characteristics

### Functional and technological characteristics of minced beef

**Water-binding capacity (WBC),**%, was determined by pressing according to the Grau and Ham method: 0.3 g of minced meat was weighed on a polyethylene disc with a diameter of 15–20 mm, after which it was transferred to an ashless filter placed on a glass plate so that the disc with minced meat was under it. Another glass plate is placed on top of the minced meat, on which a load of 1 kg is placed, and kept for 10 minutes. After that, the load and the upper plate are removed, and then the contour of the spot of pressed minced meat is traced with a pencil. The content of bound moisture (in% of the total amount of water) is calculated by the formula (1):

$$WBC = \frac{\left(m - 8.4S\right)}{m} \times 100\% \qquad (1)$$

where WBC is the content of bound moisture to total moisture,%; m is the total moisture content in the sample, mg; S is the area of the wet spot, mm$^2$; 8.4 is the empirical coefficient that reflects the ratio of the area of the wet spot to the amount of moisture that has passed into the spot.

**Fat-binding capacity (FBC)**,%, was determined according to the method described in (Tornberg, 2005). Samples of minced meat weighing 10 g were placed in pre-weighed centrifuge tubes ($m_0$), after which the tubes were hermetically sealed and kept in a water bath at a temperature of 70°C for 30 minutes.

The tubes were cooled to room temperature and centrifuged for 10 minutes at 3000 rpm. After centrifugation, the separated fat was carefully drained, and the tubes with the residue were weighed again ($m_1$, g). The fat-binding capacity (FBC,%) was calculated using the formula (2):

$$FBC = \frac{(m_1 - m_2)}{(m_0 - m_2)} \times 100\% \qquad (2)$$

where $m_0$ is the mass of the test tube with minced meat before heat treatment, g, $m_1$ is the mass of the test tube with minced meat after centrifugation, g, $m_2$ is the mass of the empty test tube, g.

**Water-holding capacity (MHC)**, **Fat-binding capacity (FBC)**, **Fat emulsion capacity (FEC),** and **Fat emulsion stability (FES)** of minced meat were determined according to the methods described in (Tsykhanovska et al., 2018). Minced meat weighing 180–200 g is placed in hermetically sealed tin cans No. 3, weighed and subjected to heat treatment according to the production regime: cooked in a water bath at 78–80°C for 1 hour, and cooled under running water to 12–15°C. The cans are then opened and the separated liquid (broth and fat) is poured into pre-weighed aluminium bottles. The mince is dried with filter paper and weighed. The weighing bottles with broth are placed in a drying cabinet and dried to a constant weight at 103–105°C. Based on these data, the moisture released during heat treatment and the moisture-holding capacity of the mince are determined. From the weighing bottles with the remains of broth and fat, the fat is extracted with 10–15 ml of solvent (chloroform: ethanol=1:2), performing the extraction for 3–4 minutes with three to four repetitions. Having determined the content of fat remaining in the mince after processing, its fat-holding capacity (FRC) is calculated.

**Water-holding capacity (**WHC),% of the minced meat weight, was determined using the formula (3):

$$WHC = [W - (\frac{m_1 - m_3}{m_2 - m})] \times 100\% \quad (3)$$

where WHC is the water-holding capacity,% of the minced meat mass; W is the moisture content of the minced meat,%; m is the mass of the minced meat, g; $m_1$ is the mass of the separated broth with fat, g; $m_2$ is the mass of the liquid before drying (i.e., the total mass of the broth before drying in a box), g; and $m_3$ is the mass of moisture contained in the separated broth after drying.

**The fat-holding capacity (**FHC),% of the minced meat mass, was determined by the formula (4):

$$FHC = [(F_{mm} - (\frac{m_1 - m_3}{m_2 - m})] \times 100\% \quad (4)$$

where FHC is the fat-holding capacity of minced meat,% to the of minced meat mass; $F_{mm}$ is the content of fat in minced meat, g; m is the mass of minced meat, g; $m_1$ is the mass of the separated broth with fat, g; $m_2$ is the mass of the liquid (broth with fat) before drying (i.e., the total mass in the box before drying), g; $m_3$ is the mass of fat released during heat treatment, g (determined after extraction from the box using a chloroform-ethanol mixture).

**The fat emulsifying stability** (FES) was determined according to the method described in (Tsykhanovska et al., 2018). Minced meat weighing 7 g is suspended in 100 ml of water in a homogenizer at a speed of 800 rpm for 1.0-1.5 minutes. 100 ml of refined sunflower oil is added and the mixture is emulsified in a homogenizer at a speed of 1500 rpm for 5 minutes. 100 ml of refined sunflower oil is added and emulsify the mixture in a homogenizer at a speed of 1500 rpm for 5 minutes is provided. After that, the emulsion is poured into 4 calibrated centrifuge tubes with a volume of 50 ml and centrifuged at a speed of 900 rpm for 10 minutes. The fat emulsifying capacity, FFC (%) was determined by the formula (5):

$$FEC = \frac{V_1}{V} \times 100\% \quad (5)$$

where $V_1$ is the volume of emulsified oil, ml; V is the total volume of oil, ml.

**Emulsion stability** (ES) was determined according to the method described in (Tsykhanovska et al., 2018). Minced meat, 10 g, was heating at 80°C for 30 minutes and cooling with water for 15 minutes. The resulting emulsion was poured into four calibrated centrifuge tubes with a volume of 50 ml and centrifuged at a speed of 500 $s^{-1}$ for 5 minutes. The volume of the emulsified layer was measured. The emulsion stability, ES,%, was calculated by formula (6):

$$ES = \frac{V_1}{V_2} \times 100\% \quad (6)$$

where $V_1$ is the volume of emulsified oil, ml; $V_2$ is the total volume of the emulsion, ml.

**Structural and mechanical properties of minced meat**

The instantaneous elastic modulus and the highly elastic modulus were determined using the Tolstoy elastoplastometer (Tsykhanovska et al., 2018). Samples of cooked minced meat with a volume of no less than 50 $cm^3$ (one-piece, without shaking) at a temperature of (4±1)°C were placed in a cuvette with a device, evenly distributing the samples and any visible excess behind a spatula. The specimen is pressed using a 2 mm diameter tip to a depth of 1 mm at a speed of 0.5 mm/s and the maximum resistance of the specimen during the first contact (peak pressure) is recorded on the load curve. The calculation of the instantaneous elastic modulus ($E_o$, Pa) is carried out according to formula (7):

$$E_o = \frac{F_{\max}}{(A \times \delta)} \tag{7}$$

where $F_{max}$ is the maximum resistance force, N; A is the contact area, $m^2$; δ is the indentation depth, m.

When determining the high elastic modulus, after reaching an indentation depth of 1 mm, hold the sample in a stationary state for 30 seconds. Record the change in the resistance force over time while holding the load. In the relaxation region of the force (from 5 to 30 s), calculate the highly elastic modulus ($E_h$, Pa) using equation (8):

$$E_h = \frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} \frac{F_{(t)}}{(A \times \delta)} \times dt \tag{8}$$

where F(t) is the resistance force at time t, N; $t_1$ and $t_2$ are the boundaries of the relaxation interval, seconds.

**Physicochemical parameters of minced meat.** Acid number (AN, mg KOH/g fat) and peroxide number (PN, mmol ½$O_2$/kg fat) were determined titrimetrically using the methods of the Association of Official Analytical Chemists (AOAC, 2017). The acid number was determined by the formula (9):

$$AN = \frac{V \times C \times 56{,}1}{m} \tag{9}$$

where V is the volume of the titrant – KOH, ml; C is the concentration of the titrant – KOH, mol/l; 56.1 is the molar mass of KOH, g/mol; m is the mass of the sample, g.

The peroxide value was determined by the formula (10):

$$PN = \frac{(V_1 - V_0) \times C \times 1000}{m} \tag{10}$$

where PN is the peroxide number, mmol of active oxygen (½$O_2$) per 1 kg of fat; $V_1$ is the volume of $Na_2S_2O_3$ solution used for titration of the sample, ml; $V_0$ is the volume of $Na_2S_2O_3$ used for titration of the blank experiment (control), ml; C is the molar concentration of $Na_2S_2O_3$, mol/l; m is the mass of the sample,

### Beef cutlets quality assessment

**Sensory quality indicators.** Sensory evaluation of the quality of beef cutlets (appearance – shape, consistency, color, taste, smell) was carried out on a 5-point scale using the profile method.

**Physicochemical characteristics of beef cutlets.** Total titrated acidity (TA), active acidity (pH units), moisture content (%) were determined by standard methods: the content of moisture was determined by the drying method; losses during heat treatment were determined by the calculation method after weighing the samples; pH was determined by the potentiometric method; total titrated acidity was determined titrimetrically: 0.1 M sodium hydroxide solution was used as the titrant, and phenolphthalein was used as the indicator. For analysis, 25.00±0.01 g of beef party were transferred to a 500 ml flask, 50 ml of distilled water was added and thoroughly ground to a pulp. Then another 200 ml of water was added, the flask was shaken for 5 min, after which the mixture was allowed to settle for 30 min and filtered. The supernatant was titrated with an alkaline solution, and the acidity was expressed in degrees. The yield of finished products was determined immediately after completion of the technological production process using formula (11):

$$X = \frac{A}{B} \times 100\% \tag{11}$$

where X is the yield of the finished product,%; A is the mass of the finished product, g; B is the mass of minced meat, g.

**Proximate analysis of beaf cutlets.** The protein content was determined by the Kjeldahl method (ISO 1871:2009, 2009), and a conversion factor of 6.25 was used to calculate the protein. The fat content was determined by the Soxhlet extraction method (ISO 11085:2015, 2015), the fat was extracted with petroleum ether with a boiling range of 40–60°C and determined gravimetrically.

The moisture and ash contents of the samples were determined according to official procedures 44-16.01 Moisture-Air-Oven (Aluminum Plate) and 08-01.01 Ash-Basic Method, respectively (AACC, 2000). Results are presented on a dry weight (dw) basis.

Vitamin content analysis was performed using a high-performance four-channel Agilent 1100 liquid chromatograph (Agilent Technologies, USA) in combination with a diode array detector (DAD) and mass spectrometry (MS) according to the method (Katsa et al., 2021; Sim et al., 2016).

The mineral composition of the cutlets was determined using an inductively coupled plasma atomic emission spectrometer Thermo iCAP 6300 Duo ICP-AES Spectrometer (Thermo Scientific, US) with operating parameters as in (Yurchenko et al., 2020).

Sample preparation was carried out according to (Bilgiçli and İbanoğlu, 2015) without modifications. Determination of iodine content in samples was carried out by galvanostatic coulometric titration using equipment (Gubskyi, 2023) according to the method (Gubskyi et al., 2015). Previously examined samples were subjected to mineralization by dry alkaline ashing to convert all chemical forms of iodine into iodide.

**The heat resistance index** (HRI), %, was determined by the iodine content in the experimental samples of beef cutlets according to the formula (12):

$$HRI = \frac{C_2}{C_1} \times 100\% \tag{12}$$

where $C_1$ is the iodine content before heat treatment (in minced meat), µg/g; $C_2$ is iodine content after heat treatment (in cutlets prepared from minced meat), µg/g.

**Evaluation of the biological value of beef cutlet proteins in vitro.** The biological value of beef cutlet proteins was assessed by the degree of hydrolysis of cutlet proteins under the action of proteolytic enzymes (pepsin and trypsin) according to the method (Brodkorb et al., 2019; Cutroneo et al., 2023; Minekus et al., 2014). A sample of 1.0 g of crushed meat cutlet was placed in a 50–100 ml test tube, 10 ml of 0.1 N HCl solution and 1 mg of pepsin/ml of solution were added (simulating the gastric phase). The mixture was then incubated at 37°C for 2 hours with occasional stirring. The pH was neutralized to ≈7.0 (by adding 0.1 N NaOH solution). The intestinal phase (trypsin) was simulated by adding 10 ml of buffer solution (pH 8.0) and 1 mg of trypsin/ml of solution, followed by incubation at 37C for another 2 hours. After that, the degree of protein hydrolysis was determined – according to the first method: the samples were centrifuged (3000 rpm, 10 minutes) and the optical density was measured in the supernatant at λ=280 nm (solution diluted 1:10); according to the second method (alternative): the method with biuret reagent or TNBS (trinitrobenzenesulfonic acid, TNBS) was used to quantitatively determine the released amino groups after hydrolysis. The calculation of biological value (hydrolysis index, HI, %) was carried out according to the formula (13):

$$HI = \frac{A_1}{A_2} \times 100\% \qquad (13)$$

where A1 is the optical density of the test sample after hydrolysis; A2 is the optical density of a standard or fully hydrolysed sample (e.g., casein or albumin).

### Microbiological analysis of beef cutlets

The following media were used to conduct microbiological studies: nutrient agar for counting the total number of microorganisms, namely the number of aerobic mesophilic and facultative anaerobic microorganisms (MAFAnM); potato-dextrose agar for the enumeration of yeast and mold; salmonella-shigellosis agar for the determination of *Salmonella* spp.; endo-agar for the determination of *Escherichia coli*; Kessler's medium for the determination of coliforms. Microbiological analysis was performed according to generally accepted methods of microbiological analysis of food products (Erkmen, 2022; Hasell et al., 2003; Olunlade et al., 2013).

### Statistical analysis

A one-way analysis of variance (ANOVA) was used for a series of parallel measurements (at least 3). Data in the tables represent the mean ± standard deviation. A p value < 0.05 was considered statistically significant. Tukey's HSD test was used to determine significant differences between means. Basic statistics and ANOVA were performed using the Minitab statistical software package version 18.1 (Minitab Inc., USA).

## Results and discussion

To select the optimal concentration of complex food additive (CFA) in the recipe for beef cutlets, a sensory assessment of cutlets with different amount of the additive, % (w/w): 0 (BC); 0.1 (B1); 0.2 (B2), and 0.3 (B3), was carried out (Table 1). The finished products were characterized by a color typical for split meat products, a soft and tender consistency, juiciness, a pleasant taste of fried meat and an expressive spicy-sea aroma.

Table 1

**Sensory assessment of the quality of beef cutlets in points**

| Characteristics | Beef cutlets | | | |
|---|---|---|---|---|
| | BC | B1 | B2 | B3 |
| Appearance (shape) | 4.4 | 4.8 | 5.0 | 4.9 |
| Consistency | 4.3 | 4.9 | 5.0 | 4.9 |
| Color | 4.2 | 4.9 | 5.0 | 4.9 |
| Taste | 4.2 | 4.8 | 5.0 | 4.7 |
| Smell | 4.2 | 4.9 | 5.0 | 4.7 |
| Overall score | 21.3 | 24.3 | 25.0 | 24.4 |

The addition of the CFA improves the shape and consistency of the cutlets, enhances their color saturation, and gives them a pleasant, rich taste and aroma, resulting in higher sensory ratings for all experimental beef cutlet samples compared to the control. According to the results of the expert assessment, the highest scores were given to the sample with the addition of 0.2% of the complex food additive from the mass of the recipe mixture. This sample was identified as the optimal one for the subsequent incorporation of the additive. in the cutlet recipe.

During the formation of a semi-finished meat cross-section product, when the geometric shape of the culinary product is set, the cohesive properties of iron oxide nanoparticles (IONPs), which are part of the complex food additive (CFA), are manifested. This facilitates the cross-linking of biopolymer molecules – proteins, carbohydrates, and lipids – leading to the formation of a stable food spatial matrix. As a result, the ratio of meat raw materials to bread in the beef cutlets recipe can be adjusted when adding the CFA. At the stage of frying experimental samples of minced beef meat enriched with the CFA, better preservation of the shape of finished products and a decrease in weight loss were recorded, which is explained by the pronounced water- and fat-retaining properties of the additive.

An increase in the adhesion of the products to the frying surface was also observed, which can be attributed to the hydration, structure-forming, and stabilizing activities of the iron oxide nanoparticles (IONPs) and laminaria proteins present in the CFA, as well as the migration of moisture from the surface layers into the deeper layers of the product (Tsykhanovska et al., 2018; Yurchenko et al., 2018).

These conclusions are confirmed by the results of studies of the influence of a complex food additive incorporation on the functional and technological properties of minced beef (BC, B1, B2, B3, B4), namely: water-binding capacity (WBC),%, fat-binding capacity (FBC),%; the level of losses during its heat treatment (losses during heat treatment),%, and the yield of finished products (yield),%) (Fig.3).

It has been shown (Figure 1) that the introduction of a highly dispersed complex food additive into minced beef at levels of 0.1%, 0.2%, and 0.3% of the recipe mixture weight increases the product's ability to retain moisture and fat by an average of 1.30 times and 1.27 times, respectively, compared to the control. This, in turn, reduces losses during heat treatment and increases the yield of finished cutlets by 5.5%. The best results were achieved with the introduction of CFA at a concentration of 0.2%; further increasing the amount of the additive to 0.3% does not significantly improve the indicators.

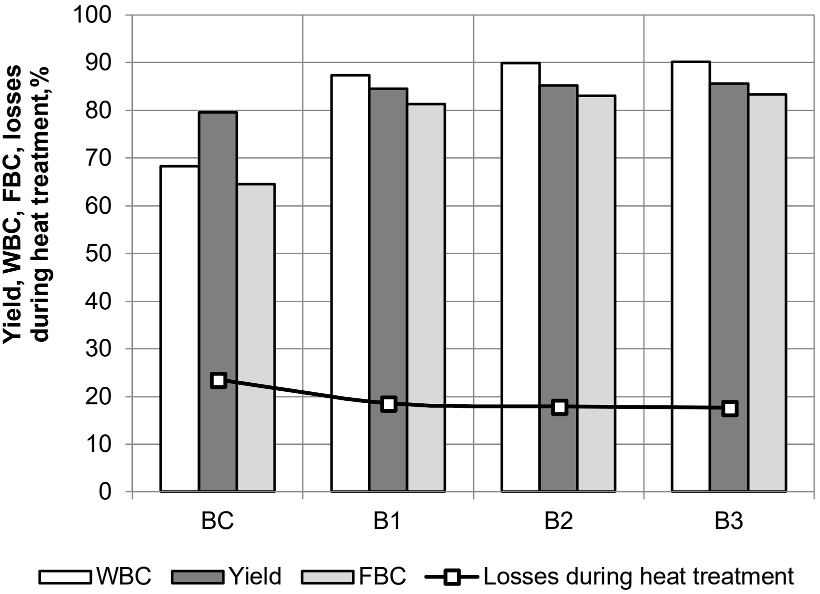
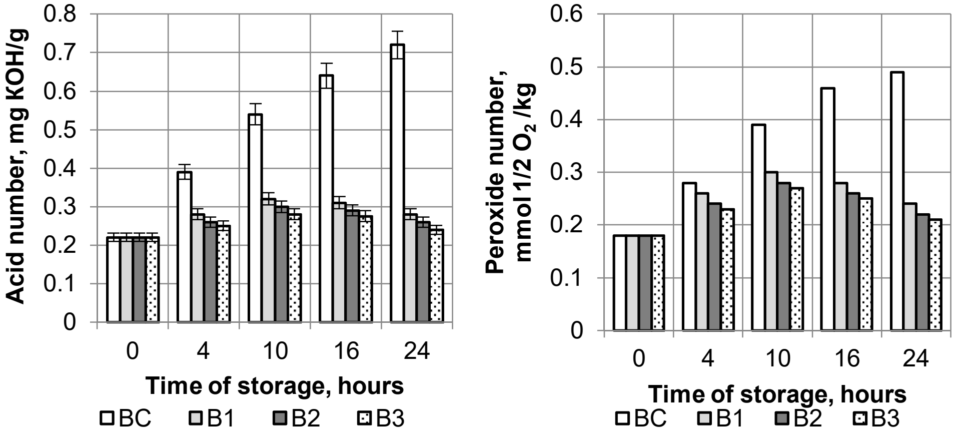


**Figure 3. The effect of a complex food additive addition in minced beef, % (w/w): 0 (BC); 0.1 (B1); 0.2 (B2), and 0.3 (B3), on its functional and technological properties. WBC, water-binding capacity; FBC, fat-binding capacity**

A study of oxidative processes in the fat component of minced beef showed the antioxidant effect of a complex food additive (CFA). CFA was added to the mince recipe in different quantities, the minced beef samples were stored for 24 hours at a temperature of (4±1)°C, and measurements of acid (AN, mg KOH/g of fat), and peroxide (PN, mmol $1/2O_2$/kg of fat), numbers were carried out during storage (Figure 4).

The values of acid number and peroxide number in all samples of minced beef during storage increase within the limits established by regulatory documentation: AN – no more than 3.5–4.0 mg KOH/g of fat (ISO 660:2020, 2020); PN – no more than 5 mmol $1/2O_2$/kg of fat (ISO 3960:2017, 2017), but increase more slowly in samples with the addition of CFA compared to the control: the AN was 2.2 times lower, and the PN was 1.6 times lower. This is due to the antioxidant properties of *Laminaria* (natural antioxidant content) and IONPs $FeO \times Fe_2O_3$. The formation of intermediate complexes between the iron atoms of IONPs and the oxygen atoms of peroxide radicals and hydrogen peroxides delays oxidative reactions. While, stabilization of fats by IONPs in a supramolecular ensemble slows down the hydrolysis of fats and reduces the accumulation of free fatty acids. In addition, due to the amphoteric nature of Fe ions, large specific surface area and high sorption activity, IONPs adsorb part of the fatty acids, which extends the shelf life and improves the quality of chopped meat products (Tsykhanovska et al., 2018).

Analysis of the physicochemical parameters of beef cutlets showed that the introduction of CFA slightly reduces the pH of finished products, i.e. increases their active acidity, which is due to the natural content of organic acids in laminaria (Table 2).



a b

**Figure 4. Oxidative processes in minced beef with complex food additive, % (w/w): 0 (BC); 0.1 (B1); 0.2 (B2), and 0.3 (B3) during storage: a – acid number; b – peroxide number.**

**Table 2**

**Physicochemical characteristics of beef cutlets**

| Indicators | Beef cutlets | | | |
|---|---|---|---|---|
| | BC | B1 | B2 | B3 |
| Active acidity, pH | 6.50±0.01$^{a}$ | 6.40±0.01$^{b}$ | 6.37±0.01$^{bc}$ | 6.35±0.00$^{cb}$ |
| Titrated acidity, °T | 0.86±0.01$^{a}$ | 1.05±0.01$^{b}$ | 1.10±0.01$^{bc}$ | 1.12±0.01$^{cb}$ |
| Moisture content,% | 35.9±1.40$^{a}$ | 36.60±0.60$^{b}$ | 37.10±0.60$^{bc}$ | 37.30±0.60$^{cb}$ |

$^{a\text{-}c}$ The mean values in the same row with different superscripts differ significantly when $p<0.05$

The presence of amphoteric iron in the iron oxide nanoparticles (IONPs), the iron-containing component of the additive, slows the increase in the active acidity (pH changes) of minced meat by 1.11–1.18 times compared to the control, including during the storage of minced beef for 72 hours at 4±1°C (Figure 5). This occurs due to the chemisorption of organic acids on the surface of IONPs and can serve as a basis for extending the shelf life of minced meat.

The addition of the CFA significantly increases the titrated acidity of minced meat by 1.22–1.27 times compared to the control, while the taste properties of the cutlets remain unchanged. Increased acidity enhances the binding and retention of water by meat proteins, thereby increasing the water-holding capacity. As a result, the proportion of bound water in the minced meat rises, improving the juiciness of the cutlets and reducing losses during frying. With increasing acidity and due to the moisture-binding properties of laminaria and IONPs, the content of free water decreases, and the total moisture content of finished products increases by 1.02–1.04 times compared to the control. In addition, with an increase in the content of the complex food additive from 0.1% to 0.3% in the samples of minced beef (compared to the control), a gradual increase in the functional and technological indicators is observed: water-holding capacity (WHC), fat-holding capacity (FHC), fat emulsion capacity (FEC) and fat emulsion stability (FES) (Table 3).

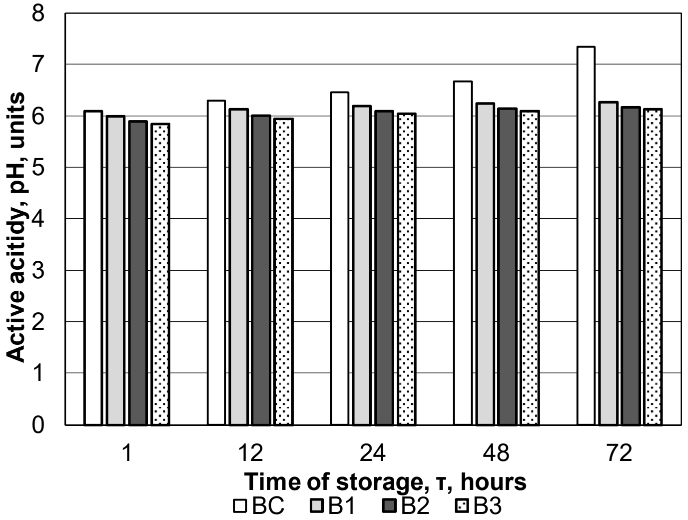


**Figure 5. Change of active acidity in minced beef with complex food additive, % (w/w): 0 (BC); 0.1 (B1); 0.2 (B2), and 0.3(B3) during storage**

**Table 3**

**Functional and technological characteristics of minced beef samples**

| Minced beef samples | Characteristics | | | |
|---|---|---|---|---|
| | WHC,% | FHC,% | FEC,% | FES,% |
| BC | 71.1±2.3$^{a}$ | 64.6±2.0$^{a}$ | 33.2±1.6$^{a}$ | 75.2±2.3$^{a}$ |
| B1 | 88.9±2.5$^{b}$ | 81.2±2.4$^{b}$ | 41.2±1.8$^{b}$ | 91.9±2.7$^{b}$ |
| B2 | 93.4±2.,8$^{c}$ | 83.5±2.4$^{c}$ | 43.6±1.8$^{c}$ | 93.4±2.9$^{c}$ |
| B3 | 94.8±2.8$^{dc}$ | 84.9±2.5$^{dc}$ | 44.4±1.9$^{dc}$ | 94.2±3.0$^{dc}$ |

$^{a\text{-}d}$ The mean values in the same column with different superscripts differ significantly when $p<0.05$

It follows from results present in Table 3 that the functional and technological indicators increase as follows: WHC by 1.33 times, FHC by 1.29 times, EC by 1.27 times, ES by 1.25 times. This is explained by the sorption and structure-forming properties of laminaria proteins and $FeO\times Fe_2O_3$ nanoparticles (Costa et al., 2021; Kireeva et al., 2024; Mamat et al., 2014; Tsykhanovska et al., 2021, 2022a, b).

Consequently, compared to the control, positive changes in the physicochemical and functional-technological properties of the minced beef and the parties made from it are observed when a complex food additive (CFA) is introduced at levels of 0.1%, 0.2%, and 0.3% of the recipe mixture mass.

In particular, water loss during frying is reduced, which ensures a higher yield of the finished product; parties hold their shape well and retain their juiciness better due to an increase in the particle of bound water in the mince. The optimal content of CFA is determined to be 0.2% of the mass of the recipe mixture.

When studying the structural and mechanical properties of minced beef samples using an elastoplastometer, the instantaneous elastic modulus and the highly elastic modulus were determined (Table 4).

**Table 4**

**Structural and mechanical properties of minced beef samples**

| Minced beef samples | Modulus of instantaneous elasticity, Pa | High-elastic modulus, Pa |
|---|---|---|
| BC | 4428±23$^{a}$ | 1596±17$^{a}$ |
| B1 | 4954±28$^{b}$ | 1769±17$^{b}$ |
| B2 | 5202±3$^{c}$ | 1827±18$^{c}$ |
| B3 | 5314±32$^{dc}$ | 1852±18$^{dc}$ |

$^{a\text{-}d}$ The mean values in the same column with different superscripts differ significantly when $p<0.05$

The addition of CFA improves these characteristics: the instantaneous elastic modulus, which reflects the ability of the minced meat to restore its original shape after loading, increases by 1.25 times compared to the control. This indicates an increased elasticity of the system due to modification by van der Waals interactions and coordination bonds with IONPs. In addition, the elastic modulus increased by 1.21 times compared to the control sample. So, the elasticity of the minced meat system is improved due to the high water-holding capacity of the complex food additive (algae-iron-containing carrier), which binds moisture and promotes the formation of solvate associates of IONPs with minced meat microparticles. As a result, a three-dimensional structural network is formed, capable of bending and returning to its original shape, which provides a soft texture and high shape-retention capacity of the beef mince. Thus, these studies provide a quantitative evaluation of the key rheological parameters required to optimize technological operations such as mixing, portioning, and forming in the production of minced meat products.

The biological value of the experimental samples of beef cutlets was assessed by the degree of digestion (hydrolysis index – HI,%) of the proteins of the beef cutlets (BC and B2) by proteolytic enzymes of the gastrointestinal tract in vitro (Figure 6).

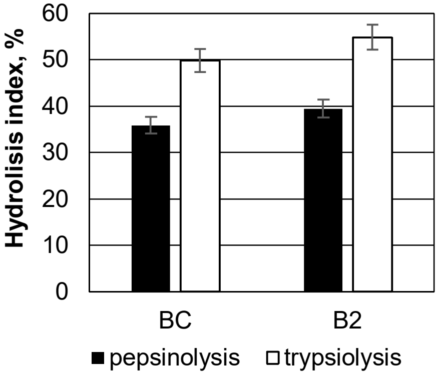


Figure 6. Enzymatic hydrolysis of proteins from beef cutlets

From Figure 6, it is evident that at both the pepsinolysis and trypsinolysis stages, the digestibility of proteins in the beef cutlets with the addition of 0.2% CFA (sample B2) exceeds that of the cutlets produced using traditional technology (control sample BC) by an average of 1.12 times. The overall digestion effect also increases by 1.12 times due to the activating effect of iron oxide nanoparticles on proteolytic enzymes of the gastrointestinal tract (pepsin and trypsin). This is due to their nano-size, significant specific volume, developed active surface, high affinity to proteins and the ability to form "protein-enzyme-nanoparticle $FeO \times Fe_2O_3$" complexes. Thus, the use of CFA in the minced meat system improves the digestion of finished proteins of meat products.

The introduction of CFA into minced meat also slows down the development of microorganisms. After 24 hours of storage at 4°C, the total number of aerobic mesophilic and facultative anaerobic microorganisms (MAFAnM) in minced B2 was $2.5 \times 10^2$ CFU/g, compared to $1.2 \times 10^3$ CFU/g in the control BC. Bacteria of the coliform group were not detected in 0.001 g; pathogenic microorganisms, including S*almonella* spp. and *Listeria monocytogenes*, were absent in 25.0 g; *Staphylococcus aureus* was not detected in 1.0 g; *Proteus* bacteria were absent in 0.1 g; and no yeast or mold fungi were detected.

Based on the results of comprehensive studies (sensory, physicochemical, structural-mechanical, microbiological), it was established that the introduction of a complex food additive in the amount of 0.1, 0.2, and 0.3% of the mass of the recipe mixture into minced beef contributes to the formation of new functional and technological properties of minced meat systems and the improvement of consumer characteristics of finished products. Similar conclusions are given in studies (Bondar et al., 2019; Cofrades et al., 2017; Espinosa-Ramírez et al., 2023; Kryzhova et al., 2021; Peñalver et al., 2020).

Analysis of the nutrient profile and nutritional value of beef cutlets (Figure 7) shows an improvement in the biological and nutritional value of B2 compared to the control BC (Table 5).

**BC** **B2**

**Figure 7. Beef cutlets: control (BC) and with 0.2% CFA (B2)**

An increase in protein content is observed, as well as enrichment of minced meat products with starch, dietary fiber, individual mineral elements and vitamins. In addition, as stated above, the proposed complex food supplement is a natural source of iodine, while the control cutlets did not contain this microelement.

**Table 5**

**Nutrient profile and nutritional value of beef cutlets**

| Nutrient profile | Beef parties | |
|---|---|---|
| | BC | B2 |
| **Macronutrients, g/100 g dry matter** | | |
| Water | 54.1±0.4$^{a}$ | 55.6±0.40$^{b}$ |
| Protein | 25.6±0.2$^{a}$ | 27.4±0.20$^{b}$ |
| Fats | 18.4±0.01$^{a}$ | 18.62±0.01$^{b}$ |
| Sugars | BDL | 0.75±0.01 |
| Starch | BDL | 1.10±0.02 |
| Cellulose | BDL | 0.96±0.01 |
| Orgainic acids | BDL | 0.40±0.01 |
| Ash | 1.8±0.01$^{a}$ | 1.93±0.01$^{b}$ |
| **Minerals, mg/100 g dry matter** | | |
| Sodium (Na) | 461.51±2.28$^{a}$ | 469.26±2.28$^{b}$ |
| Potassium (K) | 191.62±1.14$^{a}$ | 195.09±1.14$^{b}$ |
| Calcium (Ca) | 14.12±1.16$^{a}$ | 15.01±0.03$^{b}$ |
| Magnesium (Mg) | 24.46±1.04$^{a}$ | 25.54±1.04$^{b}$ |
| Phosphorus (P) | 150.08±1.03$^{a}$ | 151.16±1.03$^{b}$ |
| Iodine (I) | BDL | 0.075±0.010 |
| Iron (Fe) | 1.22±0.02$^{a}$ | 1.56±0.02$^{b}$ |
| Sulfur (S) | BDL | 0.06±0,01 |
| Zinc (Zn) | BDL | 0.05±0.01 |
| Manganese (Mn) | BDL | 0.002±0.0 |
| Copper (Cu) | BDL | 0.0011±0.0 |
| Selenium (Se) | BDL | 0.004±0.0 |
| Cobalt (Co) | BDL | 0.005±0.0 |
| Bromine (Br) | BDL | 0.01±0.0 |
| **Water- and fat-soluble vitamins, mg/100 g dry matter** | | |
| A (retinol) | BDL | 0.16±0.02 |
| E (tocopherol) | BDL | 0.17±0.01 |
| C (L-ascorbic acid) | BDL | 0.15±0.02 |
| B$_1$ (thiamine) | 0.05±0.01$^{a}$ | 0.13±0.01$^{b}$ |
| B$_2$ (riboflavin) | 0.15±0.01$^{a}$ | 0.18±0.001$^{b}$ |
| B$_3$ (PP) (niacin) | 4.04±0.01$^{a}$ | 4.29±0.01$^{b}$ |
| B$_6$ (pyridoxine) | 0.07±0.002$^{a}$ | 0.09±0.002$^{b}$ |
| B$_8$ (biotin) | 0.07±0.002$^{a}$ | 0.21±0.02$^{b}$ |
| B$_9$ (folic acid) | BDL | 0.61±0.04 |
| B$_{12}$ (cobalamin) | 0.22±0.0$^{a}$ | 0.28±0.0$^{b}$ |
| **Nutritional value** | | |
| Biological value, BV,% | 85.60±0.78$^{a}$ | 94.20±0.82$^{b}$ |
| Heat resistance index,% | BDL | 98.7±0.10 |
| Approximate calorie content, kcal/100 g | 268.62±1.02 | 287.02±1.02 |

$^{a-b}$ Mean values in the same row with different superscripts differ significantly at $p<0.05$; BDL – below detected limit.

The incorporation of the complex food additive into the beef cutlet formulation at a concentration of 0.2% (w/w) resulted in an iodine-enriched meat product containing 75±10 µg/100 g, meeting over 50% of the Recommended Dietary Allowance (RDA) for adults. Additionally, the product retained 27.8% more iron compared to the control, covering more than 10% of the adult RDA for iron. The biological value of the beef cutlets was determined by assessing the protein digestibility of the samples (BC and B2), measured as the degree of their hydrolysis (hydrolysis index, HI,%) under the action of gastrointestinal proteolytic enzymes in vitro. The obtained results indicate a high biological value of the samples: HI was 85.6% for sample BC and 94.2% for sample B2. The addition of a complex food additive also contributes to an increase in energy value by 18.4 kcal/100 g of beef cutlet with 0.2% (B2) compared to the control (BC). Therefore, enriching the beef cutlet with a complex food additive increases its nutritional value. The high heat resistance and iodine stability (98.7%) of the algal component in the complex food additive reflect the characteristics of the food matrix, which is stabilized by the formation of nanoassociates between IONPs and the biopolymers of the minced meat system at both the micro- and macro-levels.

## Conclusions

The effect of the finely dispersed complex food additive (CFA), containing iron oxide nanoparticles ($FeO \times Fe_2O_3$) and dry kelp (*Laminaria*) biomass powder, on model minced beef and the cutlets made from it was studied. It was found that adding the CFA at a level of 0.2% improves (compared to the control) the sensory indicators of the cutlets — the overall sensory score increased by 17.6% — and reduces moisture and fat losses during heat treatment, increasing the yield of the finished product by 5.5%. Incorporation of 0.2% CFA into minced beef improved its functional and technological characteristics, increasing water-holding capacity by 1.33 times, fat-holding capacity by 1.29 times, emulsifying capacity by 1.27 times, and emulsion stability by 1.25 times. At the same time, the structural and mechanical properties of the minced meat improved: the instantaneous elastic modulus increased by 1.20 times, and the highly elastic modulus by 1.16 times. Oxidative processes in minced beef with the complex food additive were suppressed, as acid and peroxide numbers were 2.2 times and 1.6 times lower, respectively, after 24 hours of cold storage compared to the control sample without CFA. The addition of CFA also increased the protein content and enriched the cutlets with dietary fiber, specific minerals, and vitamins. A beef cutlet containing 0.2% CFA provides 75 ± 10 µg/100 g of iodine, satisfying more than 50% of the recommended daily intake (RDI) for an adult.

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