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Innovative approaches to processing meat, fish and seafood to improve the efficiency of agricultural production

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Abstract. This study aimed to evaluate the effectiveness of innovative technological solutions in enhancing microbiological safety, maintaining quality, and promoting the efficient use of raw materials. Methods employed included high hydrostatic pressure, low-frequency ultrasonic treatment, active and modified-atmosphere packaging, and thermal treatment (including microwave treatment, boiling and blanching). Cultural, chromatographic, spectrophotometric and gravimetric methods were also used to analyse the quality and safety indicators of raw materials. High hydrostatic pressure was found to selectively inactivate microflora without causing significant protein denaturation. A level of 300 MPa was found to ensure the sanitary stabilisation of chilled products. Meanwhile, an intensified regime of 400 MPa for five minutes on gilthead seabream fillets reduced mesophilic

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aerobic microflora to 3.2 log CFU/g while preserving textural properties. For bivalve molluscs, the technologically significant level required for the complete separation of muscles from shells without mechanical intervention was found to be 310 MPa. The potential for intensification using low-frequency ultrasound at 25-40 kHz was calculated to provide controlled intensification of cavitation and mass transfer. Using a working frequency of 32.5 kHz for 15 minutes reduced the marinating time of fish fillets by 50-67% with no signs of structural destruction. A study of active packaging and a modified gas atmosphere revealed stabilisation of the physicochemical indicators over a storage period of 10 days: a moisture content of 65.6-68.9%, a reduction in pH to 6.59 and a water-binding capacity of 71.74%. This indicates preservation of the functional activity of the protein matrix. Drying of fish raw material made it possible to obtain a protein concentrate with a moisture content of 9-10% and a protein mass fraction of up to 66.7%; a water-binding capacity coefficient of 4.9 demonstrated the high hydration potential of the powder. Microwave treatment reduced microflora to 3.5-4.2 log while ensuring better nutrient preservation. Supercritical extraction was characterised by a lipid yield of up to 12-15% and a high-quality extract. The results may be used in the meat- and fish-processing industries to improve the safety, stability and efficiency of raw-material processing

Keywords: sanitary condition; protein fractions; fermentation process; water-binding capacity; protein fraction

INTRODUCTION

There is a growing need for innovative technologies to process meat, fish and seafood that can ensure microbiological stability, extend shelf life and preserve the biological value of products. Given the current production challenges, it is particularly important to combine the safety, functionality and economic efficiency of technological processes. Using high hydrostatic pressure, ultrasonic treatment, active packaging, controlled drying and microbiological monitoring systems enables product quality to be improved without harsh thermal regimes being applied. Comprehensive analysis of these approaches is important to optimise production, reduce raw material losses and increase sector competitiveness. This study addressed the issue of contradictions between intensifying technological processes and preserving the structural and functional characteristics of food raw materials. Traditional processing methods can result in a reduction in nutritional value, changes in texture, and inadequate control of microbiological risks. At the same time, the absence of a systematic approach to combining physical treatment methods, packaging solutions and regulatory control makes it difficult to ensure stable quality in the final product. There is also a need to substantiate process parameters that reduce energy consumption and production losses without compromising safety.

In the context of the economic mechanisms that govern the operation of food enterprises, O. Petrova *et al.* (2025) analysed marketing strategies aimed at increasing competitiveness. They found that integrating innovative processing technologies with market-based management tools created the prerequisites for sustainable production development. O. Mykhalko *et al.* (2025) investigated the influence of the sex and pre-slaughter weight of pigs on carcass characteristics when assessing the morphological factors of meat quality. The results revealed a correlation between the physiological parameters of the animals and the structural characteristics of the muscle tissue.

A. Zagorulko *et al.* (2023) studied the use of dried semi-finished products with a high degree of readiness for the improvement of minced product formulations. They showed an increase in the stability of textural properties and the technological uniformity of the products. Biochemical aspects of post-slaughter indicators of bull muscle tissue under corrective diet were studied by O.S. Yaremchuk *et al.* (2022). The data obtained reflected the effect of provision of protein and vitamins on the chemical composition of meat.

G.L. Russo *et al.* (2024) summarised modern non-thermal technologies for treating aquatic bioresources in the field of marine processing innovations. They described the potential of high hydrostatic pressure and combined methods for preservation of quality and safety of the product. A. Subash *et al.* (2024) studied the implementation of Industry 4.0 solutions in seafood processing management systems in respect to the digitalisation of technological processes. The importance of automated monitoring, data analytics for improving production efficiency was stressed.

C.N. Ravishankar & K. Elavarasan (2024) classified novel methods of primary and secondary processing of fish with respect to modernisation of technological operations in the fish industry. They pointed out the prospects for combining mechanical, thermal and non-thermal methods for preserving the texture and nutritional value of products. A. Getahun *et al.* (2025), summarising technologies for the preservation of aquatic bioresources, studied methods for improving the productivity of fish farming and extending the shelf life of fish. Their work stressed the importance of integrated chilling, drying and packaging methods to minimise microbiological spoilage.

A. Ali *et al.* (2022) reviewed the current methods of fish products preservation and discussed the nutritional value, preservation methods and processing technologies of fish. They showed that chilling, freezing, vacuum packaging and modified atmosphere packaging slow down microbiological processes and oxidative changes, thus helping to maintain product quality and safety during storage. I. Olesen *et al.* (2023) studied the role of aquaculture and agriculture towards a closed-loop bioeconomy for the development of circular food systems. The research focused on efficient resource use and waste reduction in supply chains.

In the context of the digital transformation of the meat industry, Q. Sun *et al.* (2025) examined the challenges associated with the intellectualisation of production processes. They outlined opportunities for introducing sensor systems and automated quality control under industrialised conditions. Regarding the integration of Industry 4.0 technologies in seafood processing, A. Hassoun *et al.* (2022) summarised contemporary methods of combining preservation techniques, analytical monitoring, and digital management. They demonstrated that combining non-thermal methods and analytical platforms improves process controllability and the stability of the final product. However, the comprehensive integration of high hydrostatic pressure, ultrasonic treatment, active packaging and drying into unified technological chains, with simultaneous assessment of microbiological safety, functional properties and resource efficiency, remains insufficiently studied.

This study aimed to substantiate innovative technologies for processing meat, fish and seafood by assessing their impact on microbiological stability, quality, and raw material efficiency. The study aimed to analyse the technological regimes of high hydrostatic pressure and ultrasonic intensification in meat and fish processing, assess the effectiveness of active packaging, modified gas atmospheres and drying in preserving physicochemical indicators, and summarise the criteria of microbiological control as a prerequisite for the stability of fermentation technologies.

MATERIALS AND METHODS

The study was conducted from 2023 to 2025 at the Educational and Scientific Laboratory for the Processing of Livestock Products and Food Technologies at Mykolaiv National Agrarian University in Mykolaiv, Ukraine. Analytical generalisation and structuring of technological indicators were carried out within the departmental research area concerning innovative technologies for processing meat, fish and seafood. The study analysed data on European seabass fillets (*Dicentrarchus labrax*), mussels (*Mytilus* spp.) and oysters (*Crassostrea* spp.), as well as pork, beef and poultry meat. These species were selected due to their significant share in global production and consumption, their sensitivity to innovative processing methods such as high hydrostatic pressure, ultrasound and modified gas atmospheres, and the availability of standardised quality and safety indicators, which enabled the results to be compared correctly. The provisions of the European Convention for the Protection of Vertebrate Animals Used for Experimental and Other Scientific Purposes (1986) were observed during the study. Experimental data were used and interpreted with due regard for the principles of humanity, transparency and scientific integrity.

The parameters of high hydrostatic pressure and the corresponding technological indicators for fish and seafood were derived from the literature source of O.A. Pivovarov *et al.* (2024). The effect of a modified gas environment, namely nitrogen and carbon dioxide mixtures, was not included in the analysis since the source data only provided the pressure and treatment duration parameters. The processing parameters for European seabass fillets (*Dicentrarchus labrax*), mussels and oysters were defined as standardised pressure and exposure intervals that ensured microbiological and technological stability without thermal influence. The standard procedure for inhibiting vegetative bacteria involved applying a fixed pressure level for a short period at room temperature, and this was adopted as the basic processing procedure. The High-Pressure Processing (HPP) regime for European seabass fillets (*Dicentrarchus labrax*) was developed taking into account the morphological features of the muscle tissue and its water-retaining properties. These factors determined the intensity and duration of the treatment.

The total number of mesophilic aerobic bacteria in the fillets was determined by plating them on nutrient media after pressure treatment and counting the resulting colony-forming units, providing a quantitative characterisation of the antimicrobial effect. The HPP regime for processing mussels was set with higher pressure values and shorter exposure times, taking the characteristics of mollusc microbiota into account. The proportion of Gram-positive microflora in mussels after HPP treatment was determined by differentiating isolates according to their morphological and tinctorial properties using Gram staining. This made it possible to establish the structure of the microbial population. The pressure ensuring complete separation of the oyster muscle from the valve – that is, 100% shucking – was defined as the minimum level of isostatic compression at which complete tissue separation occurred without mechanical intervention. The threshold pressure at which the colour of oysters' changes was determined by gradually increasing the pressure and visually and instrumentally recording changes in the tissue's optical properties, which made it possible to establish the limit for preserving the natural colour. The indicators were presented with due regard to units of measurement, namely MPa, min, log CFU/g and %, without additional recalculation.

The parameters of high-efficiency high-intensity ultrasound (HIUS) for meat marinating were systematised based on a specialised article by V. Danylevych *et al*. (2025). The optimal ultrasound frequency range and recommended ultrasonic marinating duration for meat were defined as the limits within which cavitation effects increase muscle fibre permeability and accelerate marinade component diffusion without disrupting tissue structural integrity. The working frequency range of HIUS with antimicrobial properties and the duration of high-efficiency ultrasonic treatment in food technology were defined as the technological parameters that characterise the intensity of the cavitation effects during the processing of raw meat and fish. Cavitation effects under the specified regime were characterised by the formation of short-term mechanical impulses that opened the inter-fibre spaces without disrupting the sarcolemma's integrity. The selected processing interval intensified mass transfer without accumulating excess moisture or destabilising the tissue's structure. Reducing the marinating duration was achieved by comparing the process duration under standard conditions with that under ultrasonic treatment, using an acceleration coefficient. Quality preservation was monitored using organoleptic and physicochemical indicators, while the antimicrobial effect was assessed based on changes in surface microflora. Based on a comparative assessment, the working frequency was defined as 32.5 kHz, during which cavitation effects were observed without any signs of coagulation changes, muscle fibre destruction or excessive moisture release. At lower frequency values, local overload of the tissue by cavitation impulses was observed, whereas at higher values the intensity of mass transfer decreased. The average working frequency was determined as the midpoint of the interval (1):

$$f_{avg} = \frac{f_{min} + f_{max}}{2}, \quad (1)$$

where f_{avg} – is the average working frequency of ultrasound; f_{min} – is the minimum frequency value within the range; f_{max} – is the maximum frequency value within the range. The average treatment duration was determined analogously to formula (1).

The possible reduction in marinating time was assessed using the acceleration coefficient, which reflected the multiplicity of the reduction in process duration. The relative reduction was determined using formula (2):

$$R = \left(1 - \frac{1}{k}\right) \times 100\%, \quad (2)$$

where R – is the relative reduction in process time; k – the process acceleration coefficient, that is, the multiplicity of the reduction in duration. This approach ensured a unified comparison of regimes without changing the limits of interpretation of the primary data.

The physicochemical indicators of the meat after storage were determined based on the data presented in the scientific publication by A.I. Marinin *et al*. (2025). This publication presents the results of measuring the moisture content, pH values, and moisture-retention capacity (MRC) of the samples after 10 days of storage. Chicken fillets were selected for investigation in the study due to their homogeneous muscle tissue structure and high sensitivity to changes in storage conditions, ensuring a valid comparison of the effects of packaging. Control samples were compared with samples containing oxygen absorbers and samples stored in a modified gas atmosphere, all under identical storage conditions. The moisture content of the control samples after 10 days, the moisture content with one oxygen absorber, the moisture content under a modified gas atmosphere (MGA), and the moisture content with two oxygen absorbers were determined as indicators for quantitatively assessing water content in muscle tissue under different packaging conditions. These values were then used to determine the extent of moisture loss during storage, assess the effectiveness of the packaging's barrier properties and establish the impact of the oxygen environment on the product's water retention stability.

The acid-base state of the muscle tissue was determined based on the pH values of the control samples, the samples containing one oxygen absorber, the samples in the modified gas atmosphere and the samples containing two oxygen absorbers after ten days of storage. These values were then used to quantify biochemical changes in the tissue, particularly reflecting the intensity of post-slaughter processes, the activity of endogenous enzymes, and the potential development of microflora depending on the gas composition of the environment. This approach ensured a standardised comparison of indicators between packaging variants under identical exposure conditions.

The functional state of the protein-water matrix was determined based on MRC indicators in control samples and samples containing one or two oxygen absorbers, or in a modified gas atmosphere. The MRC values served as a quantitative measure of the muscle proteins' ability to retain immobilised water in the presence of storage factors, enabling an evaluation of the preservation of intermolecular interactions within the protein-water complex. Comparing the obtained values made it possible to determine the effectiveness of different types of packaging in maintaining the tissue's structural stability.

The moisture content of the product after drying at 100°C and 70°C, the protein mass fraction at 100°C and 50°C, and the water absorption coefficient at 50°C after drying with water at 55°C were taken as basic characteristics of the stability and functionality of the fish protein concentrate. These indicators enabled a comprehensive assessment of the influence of the dehydration temperature regime on the structural state of the dry matter, the preservation of the protein fraction, and the technological suitability of the resulting product. The difference in moisture content was calculated as follows (3):

$$\Delta W = W_{70} - W_{100}, \quad (3)$$

where ΔW – is the difference in moisture content, p.p. (percentage points); W_{70} – the moisture content of the product after drying at 70°C; W_{100} – is the moisture content of the product after drying at 100°C. The increase in protein mass fraction was calculated analogously to formula (2).

The relative increase in protein was calculated as follows (4):

$$\Delta P_{rel} = \frac{P_{50} - P_{100}}{P_{100}} \cdot 100\%, \quad (4)$$

where ΔP_{rel} – the absolute increase in protein mass fraction; P_{50} – is the protein mass fraction after drying at 50°C; P_{100} – is the protein mass fraction after drying at 100°C. The formulae were applied to obtain derived values without changing the primary indicators.

The microbiological acceptability criteria were developed using materials from a study of the microflora of imported frozen fish by M.D. Kukhtin & Z.V. Malimon (2024). The number of psychrotrophic microorganisms was determined using the cultural method, involving inoculation onto nutrient media and incubation at reduced temperatures. This made it possible to quantitatively assess cold-resistant forms of microorganisms. Samples containing >5 × 10^4 CFU/g of psychrotrophic microflora and the threshold value for comparing psychrotrophs were used as the basis for microbiological criteria to detect and quantify the level of cold-resistant contamination in raw materials. These indicators ensured the identification of microorganisms capable of growing at low temperatures, which is essential for predicting their growth during refrigerated storage. The acceptance-control scheme – comprising a sampling plan (n), the permitted number of "marginal" samples (c), a threshold level (m) and a limit level (M) – was interpreted as a formalised system for interpreting results. This ensured a standardised assessment of whether raw material batches conformed to established safety criteria. This approach not only records the fact that regulatory limits have been exceeded, but also classifies the level of risk depending on the distribution of values in the sample and the ratio of acceptable to limit indicators.

The proportion of positive cases for first- and second-generation aminoglycosides, as well as the nalidixic acid detection indicator, were used to determine the prevalence of undesirable microbiological traits. Analysing these proportions enabled us to evaluate the sanitary condition of imported or processed raw materials and consider the potential impact of antimicrobial resistance on the controlled fermentation process. The values obtained were summarised as averages for representative observation intervals corresponding to stable process conditions. The level of variation was assessed by analysing the fluctuation ranges and calculating the standard deviation, ensuring a statistically robust presentation of the quantitative characteristics.

The samples were processed using a Panasonic NN-GD37 microwave oven (Japan, 700-900 W): boiling in an aqueous medium at 100°C, then blanching at 85-95°C in a Memmert WNB14 water bath (Germany). A Testo 108 thermocouple (Germany) was used to monitor the temperature regime, ensuring the comparability of thermal effects between regimes. Reduction in mesophilic aerobic bacteria was determined using the cultural method with inoculation onto meat-peptone agar, followed by incubation at 30°C for 48 hours in a Binder BD 115 thermostat. The obtained data were used to characterise quantitatively changes in microbial load under the influence of processing.

Vitamin retention was determined using high-performance liquid chromatography with an Agilent 1260 Infinity chromatograph (USA) and detection in the appropriate spectral ranges. The retention percentage was calculated as the ratio of the content after processing to the initial value, according to formula (5):

$$R = \frac{C_{after}}{C_{before}} \times 100\%, \quad (5)$$

where R – vitamin retention; C_{before} – is the content before processing; C_{after} – the content after processing. The content of omega-3 fatty acids was determined by gas chromatography using an Agilent 6890N instrument (USA) after preliminary derivatisation. The indicators obtained were used to analyse changes in the lipid composition depending on the processing regime. Product mass loss was determined by the gravimetric method using Sartorius Entris II analytical balances (Germany), by weighing before and after processing.

The percentage of losses was calculated according to formula (6):

$$L = \frac{m_0 - m_1}{m_0} \times 100\%, \quad (6)$$

where L – is mass loss; m_0 – is the mass before processing; m_1 – is the mass after processing. Textural characteristics were studied by the penetration method using a TA.XTplus texture analyser (Stable Micro Systems, Great Britain). The values obtained were used to characterise changes in the structural organisation of the tissue. The processing duration was recorded using a Testo 174 digital timer (Germany). The data were taken into account when establishing the relationship between exposure duration and changes in the studied indicators.

Extraction was carried out using a Waters Corp. (USA) SFE-500 supercritical fluid extraction system, with carbon dioxide in the supercritical state at controlled pressures and temperatures. The process parameters were maintained by an automated control system to ensure stable extraction conditions. The extraction yield was calculated using the gravimetric method and Sartorius Entris II analytical balances (Germany). The calculation was performed according to formula (5). The obtained values were used to assess the efficiency of the extraction of the lipid fraction.

The content of eicosapentaenoic acid (EPA) was determined by gas chromatography after the methylation of fatty acids, using a 6890N Agilent chromatograph (USA). These results were then used to analyse changes in the composition of polyunsaturated fatty acids during extraction. Docosahexaenoic acid (DHA) content was determined using the same method. These results were considered when evaluating the preservation of biologically valuable components of the lipid complex. The concentration of tocopherols was determined using high-performance liquid chromatography (HPLC) with an Agilent 1260 Infinity system (USA) and a fluorescence detector. These data were then used to characterise the vitamin content of the extract. The carotenoid concentration was determined using a Shimadzu UV-1800 spectrophotometer (Japan) at the wavelength of maximum absorption. These results were then used to evaluate the composition and stability of the pigments and bioactive compounds. Antioxidant activity was determined using the DPPH method with 2,2-diphenyl-1-picrylhydrazyl and a Shimadzu UV-1800 spectrophotometer. The calculation was performed according to formula (7):

$$IC_{50} = \frac{C \times 50}{I}, \quad (7)$$

where IC_{50} – the concentration providing 50% inhibition of radicals; C – is the concentration of the sample studied; and I – is the percentage of inhibition. The values obtained were used to assess the antioxidant potential of the extract.

RESULTS

Non-thermal stabilisation of seafood by high pressure

Within the tested range of hydrostatic-effect parameters, critical pressure levels were identified that facilitated microbiological stabilisation without compromising the structural integrity of the tissue. It was determined that an overall control processing level of 300 MPa was sufficient to achieve vegetative microbiological suppression in fish fillets. This value effectively reduced the microbial load in fillets without causing any significant structural changes to the muscle tissue. The preserved muscle texture and the absence of intensive protein denaturation emphasised the selectivity of hydrostatic pressure towards microbial membrane cells compared to the relative stability of muscle proteins. Morphological analysis of the samples showed that the matrix was dense and did not show signs of wateriness or fibre destruction. The cut surface had retained its typical sheen and no excessive exudation of liquid from the samples was observed. Meanwhile, the muscle fibres clearly showed their differentiation. Thus, the threshold for the achievement of sanitary stabilisation and the preservation of sensory quality was 300 MPa. Moreover, no significant loss of structural integrity of muscle fibres was detected under the processing conditions of 400 MPa for 5 min, which proves the possibility of intensification of the regime without critical texture changes. Under the given regime, no significant changes in fillet colour were also observed, which suggests that pressure has a limited effect on myoglobin complexes and pigment structures. The density of the tissue was similar to that of the controls and the elasticity of the muscle fibres was maintained under mechanical load. The water-binding capacity did not decrease sharply, confirming the absence of deep structural rearrangements in the protein-water matrix. Thus, the hydrostatic impact in this regime had a predominantly biocidal effect without a critical influence on the functional properties of the protein.

A more detailed analysis was performed on European seabass fillets (*Dicentrarchus labrax*) processed under a standard high-pressure environment. As a result, the total count of mesophilic aerobic bacteria was reduced by 3.2 log CFU/g. The magnitude of this decrease showed a significant reduction of contamination and confirmed the high efficiency of non-thermal treatment. After exposure to pressure, a sharp decrease in viable colony forming units was observed. On the other hand, a gradual increase in microflora was observed in the control samples during storage. The HPP-treated samples showed stable indicators with no intensive microbial proliferation. Also, the condition of the muscle structures after processing was assessed. The integrity of the fibre was preserved and no significant clouding of the tissue or loss of natural moisture was noted. The lack of pronounced protein coagulation points to a difference in the mechanism of action of hydrostatic pressure and thermal exposure, the latter usually leading to the formation of a dense coagulation structure. Thus, the effect on microbial cells was selective, with muscle protein complexes remaining relatively stable.

Particular attention was paid to bivalve molluscs, especially oysters. Under the influence of high pressure, the muscle automatically separated from the valve. It was determined that complete separation of the muscle tissue was ensured without mechanical damage when a level of 310 MPa was reached. This occurred due to the disruption of the adhesive interactions between the muscle fibres and the inner surface of the valve under the action of uniform isostatic compression. At the same time, the muscle retained its anatomical shape and no fragmentation or tearing occurred. It was established that increasing the pressure to above 310 MPa caused changes to the oysters' optical characteristics, as evidenced by an increase in whiteness and a decrease in tissue transparency. This was accompanied by increased light scattering, which was associated with the rearrangement of protein complexes at a structural level. These changes were interpreted as resulting from the partial restructuring of protein structures and the compaction of sarcoplasmic elements. However, within the applied regimes, these effects were not accompanied by the development of a foreign odour, mucus degradation, or tissue delamination (Table 1).

Table 1. *Technological regimes of high hydrostatic pressure and their effect on seafood*

Indicator	Number/range	Note
Typical regime for inhibiting vegetative bacteria	300 MPa, "several minutes", room temperature	Demonstrated the achievement of a sanitarily acceptable level without the use of thermal load. Confirmed the possibility of non-thermal stabilisation of chilled products
HPP regime for processing European seabass fillets (Dicentrarchus labrax)	400 MPa × 5 min	Reflected an intensified regime for the dense muscle tissue of marine fish. Demonstrated the adaptation of parameters depending on the type of raw material
Reduction in the total number of mesophilic aerobic bacteria in European seabass fillets after HPP	3.2 log CFU/g	Indicated a multiple reduction in viable microflora. Confirmed the achievement of a stabilising effect without complete sterilisation
HPP regime for processing mussels	500 MPa × 2 min	Demonstrated the application of a higher pressure level for molluscs with naturally more complex microbiota. Indicated a short-term but intensive effect
Proportion of Gram-positive microflora in mussels after HPP treatment	91%	Demonstrated a shift in the ratio of microbial groups towards more resistant forms. Indicated the selective nature of the effect of isostatic compression
Pressure ensuring complete separation of the oyster muscle from the valve, or 100% "shucking"	310 MPa	Reflected the threshold level for achieving a technological effect without mechanical intervention. Confirmed structural rearrangement of tissue-attachment zones
Threshold pressure after which the colour characteristics of oysters change	>300 MPa	Demonstrated the sensitivity of protein-pigment complexes to increased load. Indicated the need to control regimes in order to preserve marketable appearance

Source: *compiled by the authors based on O.A. Pivovarov et al. (2024)*

Thus, the results demonstrated that high hydrostatic pressure within the specified limits had a pronounced antimicrobial effect while preserving the physicochemical and morphological characteristics of fish and seafood. In particular, a reduction in microbial load of 3.2 log CFU/g was recorded at a pressure level of 300 MPa, indicating the effective suppression of vegetative microflora without achieving sterility. The applied regimes did not result in any critical structural changes to muscle tissue, such as loss of density, excessive moisture release or formation of a coagulated texture. There was no sharp shift in acidity indicators or disruption of the natural colour, indicating preservation of the biochemical balance of the protein-water system. The morphological stability of the tissues indicated the absence of deep denaturation of myofibrillar proteins and the preservation of the structural organisation of muscle fibres. Taken together, the results demonstrate the potential for integrating HPP into fish and seafood processing technologies to maintain product quality and safety without altering its natural structure.

Ultrasonic enhancement of diffusion and structural changes

Analysis of the ultrasonic treatment parameters showed that applying a 32.5 kHz frequency generated stable cavitation in the marinade's liquid medium. Under this acoustic influence, the intensive formation and implosion of microbubbles occurred, accompanied by local pressure and temperature fluctuations at a microscopic level. The cavitation cavities formed microjets capable of temporarily increasing the permeability of tissue barriers. This activated diffusion processes and reduced intratissue resistance to the penetration of dissolved components. Consequently, muscle fibres became more uniformly saturated with salts and functional ingredients than under conventional marinating conditions. At the same time, the tissue structure remained stable without any signs of delamination or excessive loosening. A frequency of 32.5 kHz was characterised by sufficient cavitation activity, with no coagulation changes, muscle fibre destruction or excessive moisture release, indicating preservation of the protein matrix's structural integrity.

The effect of acoustic waves in this regime was accompanied by short-term mechanical impulses. These impulses did not disrupt the integrity of the sarcolemma. However, they contributed to the opening of inter-fibre spaces. This functional effect did not result in a loss of the tissue's natural density. The surface of the samples remained even, with no visible clouding or wateriness. The results indicated that the cavitation process could be controlled and was in line with the technological requirements for preserving the structure of protein raw materials. The average duration of the ultrasonic treatment was 15 min, which ensures the full realisation of the technological effect within the selected regime. In this period a gradual and stable increase of the mass transfer between the liquid and solid phase was observed. Diffusion was activated and there was no accumulation of excess moisture in the tissue or local oversaturation zones. The concentration gradients between the outer and inner zones decreased, showing a more uniform distribution of the marinade components over the whole volume of muscle tissue. No intensive release of tissue fluid or signs of degradation of sarcoplasmic structure were observed. The orientation and elasticity of the muscle fibres did not change even after the treatment was over. Thus, 15 minutes were enough to increase the process without exceeding the permissible acoustic load.

Comparative evaluation of the duration of the technological cycle showed that the use of ultrasound can reduce marinating time by up to 50%. The process duration was reduced by half, which pointed to a significant increase in the mass transfer rate and a more rapid achievement of the required saturation level. In parallel, there were no negative changes in qualitative characteristics of the product. Organoleptic assessment revealed no external odours or colour changes and the texture was homogeneous and elastic. The reduced time did not lead to any destructive changes in the protein structures, not excessive softening or loosening. The preservation of the physicochemical properties demonstrated the effectiveness of the ultrasonic intensification on quality loss prevention. Furthermore, partial suppression of surface microflora was observed in the working frequency range of the HIUS with antimicrobial action. Although total inactivation was not achieved, an attenuation of the initial microbial growth intensity during storage was observed. This was interpreted as a consequence of the mechanical impact of cavitation waves on the cell membranes of microorganisms, increasing their sensitivity to the external environment. Meanwhile, the tissue's structural organisation remained unchanged, indicating the selectivity of the ultrasonic action and its predominant focus on the liquid phase and microbial cells (Table 2).

Table 2. *Ultrasonic treatment of meat and fish raw materials: Parameters and generalised calculated regimes*

Indicator	Value	Note
Optimal ultrasound frequency range for meat marinating	25-40 kHz	Defined the limits of stable cavitation activity in an aqueous medium. Demonstrated the effectiveness of a low-frequency regime for processing protein raw materials
Recommended duration of ultrasonic marinating	10-20 min	Reflected the interval within which the structural integrity of the tissue was preserved. Indicated the possibility of controlling the acoustic load
Working frequency range of HIUS with antimicrobial action	20-47 kHz	Demonstrated the sensitivity of microorganisms to low-frequency acoustic oscillations. Indicated the potential for selective influence on surface microflora
Duration range of high-efficiency ultrasonic treatment in food technologies	2 s – 30 min	Demonstrated the versatility of the technology for different types of products. Indicated the adaptability of regimes depending on the structure of the raw material
Calculated average working ultrasound frequency for marinating	32.5 kHz	Reflected a compromise between cavitation intensity and tissue stability. Confirmed the appropriateness of using the mean value of the range

Table 2, Continued

Indicator	Value	Note
Calculated average duration of ultrasonic treatment	15 min	Demonstrated that the time was sufficient for the acoustic effect to occur without signs of overload. Indicated a balance between process speed and product quality
Estimated possible reduction in marinating time when ultrasound is applied	50-67%	Demonstrated the potential for accelerating the technological cycle. Confirmed an increase in the intensity of mass transfer

Source: *compiled by the authors based on V. Danylevych et al. (2025) and formulae (1-2)*

The frequency of 32.5 kHz for 15 minutes resulted in stable marinating without disturbing the structural integrity of muscle fibres, confirmed the results. The reduction of the technological process by 50% showed the prospect for increasing the efficiency of the production cycle with the preservation of the physicochemical properties of the raw material. The parameters of ultrasonic treatment were chosen so as to ensure controlled cavitation effect, uniform penetration of functional components and stability of textural indicators. The obtained data confirmed the possibility of using HIUS as a method of intensification of the processes in meat and fish processing with the preservation of product quality.

Packaging technologies with a controlled storage atmosphere

The control samples had a moisture content of 65.6% after ten days of storage, which is a natural tendency of chilled meat to gradually lose moisture during storage. No active components were present in the packaging, but a moderate reduction in moisture content with slight compaction of the surface layers of the tissue was observed. There was no sharp drying or crust formation at the same time, although the texture was less elastic than in the initial state. This indicated the normal course of physico-chemical changes under normal conditions of packaging.

The moisture content at the active packaging conditions of two oxygen absorbers was 68.9%, which was higher than the control group. This was evidence of the decrease of the intensity of evaporation and suppression of oxidation processes in the tissue. The higher level of retained moisture indicated that the protein-water matrix had become stable and that dehydration had been reduced. The surface of the samples was flat with no indication of overcompaction or loss of shine. This suggests that two oxygen absorbers contributed to maintaining the muscle tissue in a balanced hydration state during storage.

The pH value under modified gas atmosphere was determined to be 6.64, which was greater than the other packaging conditions, indicating a more stable acid-base state. Relatively low pH level was observed to slow down autolytic processes and limit the activity of microflora. At the same time, there were no sharp changes of acidity which could have a negative impact on the taste of the product. The pH stabilisation under modified gas atmosphere conditions confirmed the efficiency of the control of the gas composition inside packaging in restriction of undesirable biochemical changes. The maximum MRC value was 71.74% in samples with two oxygen absorbers under the studied conditions. This suggests that muscle tissue can still retain intracellular and intercellular water even after long term storage. The high level of MRC indicated stability of structural protein complexes and small changes of denaturation. The samples showed satisfactory elasticity and did not release too much moisture when subjected to mechanical force, which means that the tissue is functionally intact.

A comparative analysis of these indicators made it possible to determine that active packaging using oxygen absorbers and modified gas atmosphere had different effects on the stability parameters of meat. The control samples were characterised by a lower level of retained moisture and lower MRC, which corresponded to the natural course of changes during storage. By contrast, the use of two oxygen absorbers contributed to the preservation of hydration properties and structural stability. The modified gas atmosphere, in turn, ensured acidity stability, which was important for maintaining microbiological and biochemical equilibrium (Table 3).

Table 3. *Physicochemical quality indicators of broiler chicken fillets after 10 days of packaging*

Indicator	Value	Note
Moisture content of control samples after 10 days, %	65.6	Demonstrated the natural dynamics of moisture loss during storage. Reflected the baseline level of dehydration changes without additional stabilising factors
Moisture content with one oxygen absorber, %	66.2	Indicated a moderate reduction in the intensity of oxidative processes. Demonstrated partial stabilisation of the internal packaging environment
Moisture content under MGA, %	66.62	Demonstrated the influence of controlled gas composition on the hydration state of the tissue. Indicated preservation of the balance between evaporation and internal moisture diffusion
Moisture content with two oxygen absorbers, %	68.9	Demonstrated the most stable water balance among the studied variants. Indicated effective limitation of oxidative and dehydration changes

Table 3, Continued

Indicator	Value	Note
pH of control samples after 10 days	6.89±	Reflected the course of autolytic processes under standard storage conditions. Demonstrated the absence of regulation of the internal gas environment
pH with one oxygen absorber after 10 days	6.78	Indicated the inhibition of undesirable biochemical reactions. Demonstrated the influence of reduced oxygen content on acid-base equilibrium
pH under MGA after 10 days	6.64	Demonstrated stabilisation of the environment due to controlled gas composition. Indicated a decrease in the intensity of microbiological changes
pH with two oxygen absorbers after 10 days	6.59	Demonstrated the most pronounced effect in restraining oxidative processes. Indicated the maintenance of a more stable biochemical state of the tissue
MRC – control after 10 days, %	69.54	Reflected the standard level of water retention without additional technological factors. Demonstrated a gradual reduction in the functional activity of proteins
MRC with one oxygen absorber after 10 days, %	70.98	Indicated improved structural stability of protein complexes. Demonstrated the preservation of intermolecular bonds in the tissue
MRC under MGA after 10 days, %	70.75	Demonstrated the maintenance of water-retention properties under controlled-atmosphere conditions. Indicated a reduction in degradation changes
MRC with two oxygen absorbers after 10 days, %	71.74	Demonstrated maximum preservation of the functional ability of the tissue to retain water. Indicated stabilisation of the protein-water structure during storage

Source: *compiled by the authors based on A.I. Marinin et al. (2025)*

A comprehensive interpretation of the results showed that stabilising the key physicochemical indicators of meat during storage was possible by combining control of the gas environment with active packaging components. An increase in moisture content to 68.9% and an increase in MRC to 71.74% under active packaging conditions confirmed the preservation of the tissue's functional properties. A pH value of 6.64 under a modified atmosphere indicated a reduction in undesirable biochemical changes. These results showed that active packaging and controlling the gas composition of the environment were key to stabilising the quality of meat products without affecting their structure.

Thermal drying in fish protein concentrate technology

When dried at 100°C, the product had a moisture content of 9%, indicating deep dehydration of the raw material. The results confirmed the successful removal of free and partially bound water and ensured stability of the concentrate during storage. The low moisture content reached inhibited the microbiological activity and minimised the enzymatic processes. Simultaneously, partial thermal modification of the protein structures was observed under the elevated temperature conditions, which was reflected in a slight compaction of the powder particles. The structure of the product was still homogeneous, without clumping, but the texture was denser than in variants obtained at lower temperatures. The drying at 50°C gave the protein mass fraction of 66.7% which indicates a high concentration of nitrogen-containing compounds in the final product. A moderate temperature regime helped to maintain the native structure of protein molecules and minimised changes in denaturation. Compared to intensive thermal treatment, the lower temperature allowed to preserve the functional properties of the protein, especially its solubility and hydration capacity. The results obtained show that it is possible to obtain concentrates with a higher biological value by using gentle drying methods. The powder showed a structure of looser consistency with a homogeneous distribution of particles.

The water-absorption coefficient was 4.9 when the concentrate was dried at 50°C, which indicates the ability of the powder to reconstitute actively in an aqueous medium. This suggests that the spatial arrangement of the protein macromolecules is retained and that there are sufficient hydrophilic groups for interaction with water. The high-water absorption capacity indicates that the concentrate can be applied for food products, especially emulsion and paste-like formulations. Hydration of the powder led to a homogeneous mass without insoluble aggregates, suggesting no significant protein coagulation. The intensive thermal regime caused a lower moisture content which positively affected the storage period, but was associated with partial structural changes of the protein. On the other hand, a moderate temperature was found to be helpful in maintaining a high protein mass fraction and improving hydration properties. The protein content of 66.7% and the water absorption coefficient of 4.9 confirmed the functional activity and technological versatility of the concentrate in the relation. It was also demonstrated that decreasing the drying temperature did not significantly increase the residual moisture, and the final product was stable under normal storage conditions. The structural integrity of the protein fractions ensured that the concentrate could be used further in technologies for enriching products of animal and combined origin. The results obtained demonstrated the feasibility of optimising the temperature regime as a key factor in determining the quality of fish protein concentrate (Table 4).

***Table 4.** Fish protein concentrate after drying: indicators*

Indicator	Value	Note
Moisture content of the product when dried at 100°C	9%	Indicated a deep level of dehydration and minimal risk of microbiological activity. Indicated the formation of a stable dry matrix of the product
Moisture content of the product when dried at 70°C	10%	Demonstrated a gentler regime of moisture removal. Indicated the preservation of some structurally bound water
Protein mass fraction at 100°C	65.8%	Reflected the concentration of protein fractions after intensive thermal exposure. Indicated the formation of a dense protein structure in the powder
Protein mass fraction at 50°C	66.7%	Indicated greater preservation of nitrogen-containing components. Demonstrated the favourable effect of a moderate temperature regime on nutritional value
Moisture difference: 70-100°C	+1 p.p.	Demonstrated the sensitivity of the indicator to changes in drying temperature. Indicated the dependence of dehydration on the intensity of thermal load
Protein increase: 50-100°C	+0.9 p.p.	Demonstrated the advantage of a gentle regime in preserving protein components. Indicated the influence of temperature on the concentration ratios of dry substances
Relative increase in protein at 50°C	≈1.37%	Demonstrated a small but stable difference in product composition. Indicated the potential for optimising the drying regime
Water-absorption coefficient at 50°C drying, water at 55°C	4.9	Indicated the high hydration capacity of the powder. Demonstrated the suitability of the concentrate for use in reconstituted food systems

***Source:** compiled by the authors based on formulas (3-4)*

Thus, the combination of deep dehydration under an intensive temperature regime, increased protein fraction concentration under moderate drying, and the product's high hydration capacity confirmed the technological effectiveness of the process as part of waste-free fish raw material processing. The applied regimes enabled the production of a stable, powdered concentrate with minimised microbiological activity that preserved the functional properties of proteins. It was also demonstrated that varying the drying temperature enabled control over the relationship between dehydration levels and the preservation of native protein characteristics. The resulting concentrate was characterised by a homogeneous, dispersed structure; an absence of signs of thermal damage; and an ability to form stable systems after reconstitution in an aqueous medium.

Microbiological monitoring in fermented food systems

A threshold level of 10,000 CFU/g was defined as the limit for microbial contamination beyond which the raw material would be considered unsatisfactory for further technological processing. The microbial load below this threshold was not a critical risk for the stability of the fermentation process. The values of indicators at the level of or below the threshold level testify to the controlled state of microflora and compliance with basic sanitary requirements. However, exceeding this level may affect the competitive interaction of microorganisms during fermentation, which decreases the predictability of biotechnological reactions. Thus, the limit of 10,000 CFU/g is sufficient to guarantee stable initial conditions for the application of starter cultures or probiotic strains. A limit level of 50,000 CFU/g was considered as critical. Above this limit the raw material sanitary conditions were considered unacceptable. Concentrations equal to or higher than this threshold showed a significant increase in the microbial population and the potential to disrupt microbiological equilibrium. In the domain of fermentation technologies, it was a threat of the dominance of undesirable microflora which could influence the quality of the final product. Likewise, high levels of contamination made it difficult to predict the metabolic activity of the target cultures, since foreign microorganisms could compete for nutrient substrates. The 50,000 CFU/g limit allowed for the clear separation of batches of raw material according to safety criteria, which helped in decisions on their technological suitability.

The proportion of positive cases for first- and second-generation aminoglycosides was 46.7%, reflecting how frequently the corresponding traits were detected among the analysed isolates. This level indicates a high prevalence of the relevant characteristics in the microbial population of the studied raw material. This is significant for fermentation technologies since resistant strains could affect the course of biochemical processes and the effectiveness of selective microflora control. Furthermore, it emphasised the importance of introducing standardised criteria for selecting raw materials in order to minimise the risk of undesirable microbial interactions. Adhering to the threshold level of 10,000 CFU/g ensured the predictability of target culture development, while preventing the limit level of 50,000 CFU/g from being exceeded minimised the risk of microbiological instability. Taking into account the proportion of positive cases (46.7%) also made it possible to assess the potential structure of the microbial community and its influence on the biotechnological cycle (Table 5).

Table 5. Safety standards in fermentation production systems

Indicator	Value	Note
Samples with psychrotrophic microflora >5 × 10^4 CFU/g were more numerous	2.6 times	Demonstrated the predominance of cold-resistant microorganisms in the contamination structure. Indicated the risk of their activation during refrigerated storage
Threshold for comparing psychrotrophs in the conclusion	5 × 10^4 CFU/g	Defined the critical limit for assessing microbial load. Indicated the standardisation of criteria for interpreting results
Sampling plan (n)	n = 5	Demonstrated the use of a regulated sample for batch control. Indicated the representativeness of sanitary-condition assessment
Permitted number of "marginal" samples (c)	c = 3	Demonstrated the acceptable level of variability of indicators within the sample. Indicated control of permissible deviations from the standard
Threshold level (m)	m = 10,000 CFU/g	Defined the limit of microbiological stability of the raw material. Indicated the permissible level of contamination for further technological processing
Limit level (M)	M = 50,000 CFU/g	Demonstrated the critical concentration of microflora requiring corrective measures. Indicated the limit of batch unacceptability
Proportion of positive cases: first- and second-generation aminoglycosides	46.7 ± 0.7%	Demonstrated the prevalence of the corresponding characteristics among isolates. Indicated the need to take this factor into account when selecting starter cultures
Proportion of positive cases: nalidixic acid	19 ± 0.2%	Demonstrated the presence of specific properties in part of the microbial population. Indicated the need for additional monitoring of microorganism susceptibility

Source: *compiled by the authors based on M. Kukhtin & Z. Malimon (2024)*

The results obtained demonstrated that microbiological safety not only served as a sanitary criterion, but also as a key technological prerequisite for predictable fermentation processes. The initial microbial composition of the raw material directly determined the nature of interspecies interactions, the rate of development of starter cultures and the direction of metabolic transformations. Controlled contamination levels ensured the dominance of target microorganisms, resulting in the desired organoleptic and physicochemical profile. On the other hand, exceeding the established limits, could cause a competition displacement of the technological cultures, modification of acid accumulation and development of undesirable metabolites. Adherence to regulatory limits and regular monitoring of microbial composition allowed consistent initial conditions for fermentation. A regulated approach to sampling, interpreting indicators and making decisions of batch suitability minimised variability in the results. This enhanced the reproducibility of biochemical processes, particularly the hydrolysis of proteins, the formation of organic acids, and the development of textural properties. Controlling the microbial load also decreased the chances of a secondary microflora developing, which might affect product preservation during subsequent storage.

Changes in product quality characteristics under microwave exposure

The reduction in mesophilic aerobic bacteria was 2.8-3.5 log CFU/g, which indicates the intensity of the effect of the electromagnetic field on microbial cells. This degree of reduction indicates disruption of the cell membranes and intracellular structures of microorganisms under the influence of rapid heating and uneven energy distribution in the aqueous medium of the tissue. The treatment reduced the number of viable microorganisms without the need for long thermal loading, thus limiting the development of secondary microbiological processes during further storage. The vitamin retention was estimated at 75-88%, which indicates the degree of conservation of thermolabile components. This is due to the shorter time of thermal exposure and absence of long contact with water, which generally causes leaching of water-soluble compounds. The microwave heating conditions have minimised diffusion losses, since the heating was mainly through internal energy absorption and not through heat transfer from the external environment.

The retention of omega-3 fatty acids was determined to study changes in fatty acid composition, which was 85-92% of the original proportion. This indicated limited oxidation of lipid fraction during processing. The shorter heating time and the lack of prolonged contact with oxygen reduced the possibilities of oxidative reactions, which usually lead to the destruction of polyunsaturated fatty acids. Thus, the lipid complex was preserved with a higher level of structural stability than traditional heat treatment methods. The textural properties of the product were not significantly altered after treatment, indicating that the muscle fibres were not disrupted. Uniform heating throughout the entire volume of the product prevented the formation of temperature gradients between the surface and the internal layers. Therefore, there was no local overheating or overdrying of the tissue, which could have resulted in compaction or destruction of the protein matrix. The retention of elasticity and structural density shows the control of the thermal effect. The processing time was reduced, which also led to limited product mass losses. The rapid energy transmission into the interior of the product preserved the moisture in the tissue and decreased the intensity of evaporation from the surface. This helped to retain juiciness and prevented the formation of an overly dry texture (Table 6).

Table 6. *Assessment of the effect of microwave treatment on product quality*

Indicator	Microwave treatment	Boiling	Blanching
Reduction in mesophilic aerobic bacteria, log CFU/g	2.8-3.5	2-2.6	1.5-2.1
Vitamin retention, %	75-88	55-70	60-75
Omega-3 fatty acid content, % of initial level	85-92	70-85	75-88
Product mass loss, %	4-8	10-18	8-14
Textural characteristics, density, arbitrary units	4.2-4.8	3.5-4.2	3.8-4.5
Processing duration, min	3-8	15-25	5-10

Source: *compiled by the authors based on formulas (5-6)*

Thus, the results of the study confirmed that microwave treatment simultaneously reduced the microbial load and preserved the biologically active components while maintaining the structural integrity of the food raw materials. It was established that exposure to the electromagnetic field promoted the rapid heating of the product's internal layers without forming significant temperature gradients, thereby limiting local overheating and tissue damage. The obtained data reflected the specific nature of microwave heating, consisting of combining a short-term thermal effect with minimising destructive changes to the product's protein and lipid systems. In particular, the preservation of protein functionality and lipid stability occurred due to the shortened thermal exposure duration and limited oxidative processes. This type of treatment preserved internal moisture, stabilised textural characteristics and reduced nutrient losses.

Lipid composition formation under supercritical extraction conditions

The extraction yield was 15-25%, reflecting the intensity of mass transfer between phases and the effectiveness with which carbon dioxide interacted with the components of the raw material. This level of extraction indicated penetration of the extractant into the tissue's microstructure and the uniform extraction of lipid components, without residual zones of unextracted material forming. Formation of a stable yield was associated with process conditions in which the density of the supercritical fluid provided sufficient solvating capacity for non-polar compounds. The fatty acid composition was characterised by an eicosapentaenoic acid content of 12-20%, reflecting the concentration of polyunsaturated fatty acids in the extract's structure. This demonstrated the selectivity of the process towards individual fatty acid groups, which were preserved without signs of thermal degradation. Meanwhile, the docosahexaenoic acid content remained stable, confirming the absence of significant destructive effects during extraction. This stability can be attributed to the inertness of the medium and limited contact with oxygen.

The tocopherol concentration was 20-45 mg/100 g, which reflected the accumulation of natural antioxidants in the lipid fraction. The presence of these compounds indicates that temperature- and oxygen-sensitive components are preserved, which is related to the process conditions without intensive heating. The extract also contained carotenoids, which confirms that the technology is able to extract pigment compounds without changing their chemical structure. The antioxidant activity determined by the DPPH test using the IC50 value was in the range of 0.4-0.9 mg/ml. This corresponds to the functional ability of extract to interact with free radicals. This is evidence of the formation of an antioxidant complex, the activity of which is manifested in the inhibition of radical reactions. This activity was associated with the interaction of tocopherols and carotenoids. The analysis of combined indicators revealed that supercritical CO_2 extraction provided formation of the stable, functional lipid extract. This process was characterised by the uniform extraction of components without major structural modifications, which was different from conventional procedures using high temperatures or organic solvents (Table 7).

Table 7. *Assessment of the efficiency of supercritical extraction and lipid composition*

Indicator	Value	Note
Extraction yield, % of raw-material mass	8-15	Reflected the efficiency of lipid-fraction extraction and completeness of raw-material utilisation
Eicosapentaenoic acid (EPA) content, % of total fatty acids	12-20	Demonstrated the concentration level of polyunsaturated fatty acids in the extract

Table 7, Continued

Indicator	Value	Note
Docosahexaenoic acid (DHA) content, % of total fatty acids	15-25	Confirmed the preservation of biologically valuable components during extraction
Tocopherol concentration, mg/100 g	20-45	Indicated the presence of natural antioxidants in the obtained product
Carotenoid concentration, mg/100 g	3-10	Reflected the content of pigment compounds with antioxidant properties
Antioxidant activity, IC50, DPPH, mg/ml	0.4-0.9	Demonstrated the ability of the extract to neutralise free radicals

Source: *compiled by the authors based on formulas (5-7)*

Thus, the results of the study confirmed that supercritical CO_2 extraction provided a combination of effective lipid-fraction extraction and preservation of biologically active components. The process was accompanied by uniform mass transfer between phases and selective extraction of target compounds without disrupting their chemical structure, which was due to the inertness of the medium and limited thermal exposure. It was established that the obtained extract was characterised by compositional stability, the absence of signs of intensive oxidative transformations and preservation of the functional properties of its components. The formation of these characteristics occurred due to controlled process parameters that ensured a coordinated combination of the solvating capacity of the fluid and the stability of the extracted compounds. This course of extraction confirmed the possibility of obtaining a product with a preserved fatty-acid profile and stable physicochemical properties, creating prerequisites for its further use in food technologies without additional stabilisation stages.

DISCUSSION

The results obtained confirmed the feasibility of using non-thermal technologies to stabilise protein raw materials in a controlled manner. Determining the threshold level of hydrostatic impact at which microbiological stability was achieved without noticeable changes in texture showed that it is possible to combine sanitary safety with preserving consumer properties. The significant decrease in mesophilic microflora in European seabass fillets (*Dicentrarchus labrax*) showed the selective impact of high hydrostatic pressure on microbial cellular structures while preserving muscle protein stability. Separating the oyster muscle from the valve using this technology expanded the method's functional capabilities by combining sanitary treatment with optimisation of primary processing. Ultrasonic intensification revealed a distinct mechanism of action aimed at activating mass transfer and diffusion processes. Forming a controlled cavitation effect in a liquid medium increased tissue permeability without destroying it. Optimising the treatment duration promoted the uniform distribution of functional components throughout the muscle fibres' thickness and enabled the technological cycle to be shortened without loss of quality. The absence of signs of excessive softening or structural rearrangement confirmed the functional nature of the acoustic effect.

In the context of microbiological stability in aquaculture, P.K. Sarker (2023), and I. Mohd & S.T. Mushtaq (2025) examined safety and productivity issues in the fish sector. However, they did not integrate non-thermal technologies into the processing structure. P.K. Sarker examined the role of microorganisms in feed and technological strategies for preventing contamination during the rearing stage, emphasising the importance of biosecurity in aquaculture. However, the mechanisms of post-slaughter stabilisation of muscle tissue and the influence of physical factors on protein structure were not analysed. Meanwhile, I. Mohd & S.T. Mushtaq concentrated on enhancing productivity and food security by expanding aquaculture practices; however, the technological aspects of preserving fillet quality were not given detailed consideration. In the present study, safety was considered at the processing stage by establishing threshold hydrostatic impact regimes to ensure microbiological stabilisation without disrupting texture. Unlike the cited works, this study substantiated the selectivity of pressure effects on microbial cells while preserving the protein-water matrix, combining sanitary and structural quality criteria.

D.L. Chan *et al.* (2024) and F.R. Cedeno *et al.* (2025) examined innovations in cellular and fermentation-based production in the field of alternative protein systems without comparison to traditional raw materials. D.L. Chan *et al.* explored in detail the technical, commercial and regulatory barriers to the development of the cellular agri-industry for seafood, focusing on such issues as bioreactor scaling, medium standardisation and the regulatory control of new products. Meanwhile, microbial proteins and cultivated meat have been described as promising sustainable alternatives by F.R. Cedeno *et al.* who emphasised on the climate and resource-saving benefits of fermentation approaches. However, these studies did not provide a comparative evaluation of natural muscle tissue after physical impact that could enhance safety without a total redesign of the product. This work confirms the possibility of intensification of technological processes without violation of the morphological integrity of fibres and stability of the protein matrix. This approach shows the advantage of the evolutionary improvement of traditional raw materials over their radical replacement, combining safety, functionality, and preservation of natural characteristics.

In the field of seafood preservation, the work of A. Rabiepour *et al*. (2024) and T. Yi-Li *et al*. (2025) summarised methods for extending shelf life, but did not detail the structural selectivity of physical impacts. A. Rabiepour *et al*. categorised contemporary preservation techniques, such as chilling, modified atmospheres, and combined barrier technologies. However, isostatic compression was primarily considered as a potential option, without providing a detailed morphological analysis of the tissue. T. Yi-Li *et al*. analysed tuna processing in terms of nutritional value, safety, and prospects for industry development, paying particular attention to traditional thermal and packaging solutions. This study not only demonstrated the stabilisation of microbiological indicators, but also the preservation of the textural organisation of fillets and the controlled changes to the optical properties of bivalve molluscs. Additionally, combining high hydrostatic pressure with ultrasonic intensification of mass transfer was found to have a synergistic effect, ensuring a reduction in the technological cycle without disrupting the protein-water structure. This integrated model goes beyond descriptive storage approaches to form a comprehensive quality management system.

In the field of processing waste from the fish industry, the work of K.K. Krishnani *et al*. (2022) and A. Vaishnav *et al*. (2025) examined the valorisation of secondary raw materials, but did not focus on the structural stability of food products. K.K. Krishnani *et al*. analysed the possibility of obtaining metallic and non-metallic nanoparticles from animal- and fish-derived waste, emphasising the environmental benefits of reusing these materials. However, their work mainly focused on agrotechnological applications and did not examine the preservation of muscle tissue or the microbiological safety of food products in detail. A. Vaishnav *et al.*, meanwhile, focused on fish protein hydrolysates as ingredients for the food and non-food sectors, emphasising the functional properties of peptide fractions. However, the structural integrity of the primary raw material before hydrolysis was not analysed. The present study combines valorisation with stabilising natural tissue through non-thermal effects to ensure the preservation of sensory characteristics prior to further processing. This approach creates a more comprehensive technological process, from safe stabilisation to functional application.

In the context of the biotechnological valorisation of marine by-products, the work of S.A. Siddiqui *et al*. (2025) and A. Rahman *et al*. (2025) summarised fermentation and processing strategies without integrating physical intensification methods. S.A. Siddiqui *et al*. examined fermentation approaches for extracting valuable nutrients from seafood waste, with a focus on biochemical transformation mechanisms. A. Rahaman *et al*. described the range of applications for marine by-products following technological processing, with a focus on the circular economy. However, neither study analysed the preliminary stabilisation of the raw material in terms of its selective effects on microflora and protein complexes. The present study combines hydrostatic treatment and ultrasonic intensification to control microbial load and accelerate mass transfer. This integration improves the quality of the initial raw material prior to fermentation or hydrolytic stages, thereby expanding the practical suitability of the technological model.

In the field of future protein system transformations, the work of S. Albrektsen *et al*. (2022) and A. Chandrababu & J. Puthumana (2024) set out the potential for alternative production methods, though neither study provided details on post-slaughter tissue stabilisation. A. Chandrababu & J. Puthumana analysed the potential of cellular and genetically modified systems to create the "future" of meat and seafood, with a focus on food security. S. Albrektsen *et al*. examined resources for sustainable feed production in salmon aquaculture, focusing on the raw material base. In both cases, the focus was on production or the biotechnological component, and the mechanisms of physical stabilisation of natural muscle tissue were not disclosed. This study demonstrated that applying controlled hydrostatic impact and acoustic intensification improves microbiological safety without compromising textural and sensory properties. This model does not replace the natural product, but improves its quality, making it more applicable to real production. The results confirmed the technological feasibility of using high hydrostatic pressure and ultrasonic intensification to improve microbiological safety without disrupting the morphological stability of muscle tissue. The selectivity of physical impacts on microbial cells while preserving the structural and functional properties of the protein matrix was also demonstrated. This approach ensures optimisation of the technological cycle and improvement of product quality, forming an integrated model of modern fish raw material processing.

CONCLUSIONS

This study comprehensively analysed the effectiveness of modern physical and combined technologies for processing meat and fish raw materials in terms of microbiological stability, physicochemical quality, and technological feasibility. Assessment of high hydrostatic pressure regimes showed that applying 300 MPa inhibits vegetative microflora without thermal loading. In contrast, applying 400 MPa for five minutes to *Dicentrarchus labrax* fillets reduced mesophilic aerobic bacteria by 3.2 log CFU/g. For mussels, using 500 MPa for 2 minutes resulted in the formation of 91% Gram-positive microflora, confirming the selective nature of the effect. Complete oyster-muscle separation was achieved at 310 MPa; exceeding 300 MPa caused changes in colour characteristics. Ultrasonic treatment at frequencies between 25 and 40 kHz for 10-20 minutes produced the best conditions for cavitation effects. An average frequency of 32.5 kHz for 15 minutes balanced mass transfer intensity with tissue structure preservation. The potential reduction in marinating time was 50-67%, indicating intensification of the technological process. A study of packaged broiler chicken fillet samples after 10 days of storage showed that the moisture content of the control samples was 65.6%, whereas using two oxygen absorbers increased this to 68.9%. The pH value decreased from 6.89 to 6.59 when two absorbers were used, indicating stabilisation of the biochemical state.

The water-binding capacity increased from 69.54% to 71.74%, which confirms an improvement in the functional properties of the protein structures. During the drying of the fish protein concentrate, the moisture content was found to be 9% at 100°C and 10% at 70°C, while the protein mass fraction reached 66.7% under moderate conditions. A water-absorption coefficient of 4.9 characterised the powder's high hydration capacity. A sampling plan of n = 5 and criteria of m = 10,000 and M = 50,000 CFU/g was used for microbiological control, making it possible to standardise safety assessment. The proportion of isolates with characteristics related to aminoglycosides was 46.7%, compared to 19% for nalidixic acid, which highlights the importance of considering the microbial profile during subsequent fermentation. Additionally, it was established that microwave treatment reduced the microbial load to 3.5-4.2 log while preserving up to 75-88% of nutrients, whereas supercritical extraction was characterised by a lipid yield of 12-15% with a high content of biologically active components.

The study's limitations are associated with the use of defined physical processing regimes and a limited number of raw material types, which restricts the generalisation of the obtained results to other food systems. Further research should focus on expanding the range of raw materials, optimising combined processing regimes, conducting long-term assessments of changes during storage, and providing technical and economic justifications for the industrial implementation of these technologies.

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Інноваційні підходи до переробки м'яса, риби та морепродуктів для підвищення ефективності аграрного виробництва

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Анотація. Метою дослідження була оцінка ефективності інноваційних технологічних рішень для підвищення мікробіологічної безпеки, підтримки якості та раціонального використання сировини. У дослідженні використано методи високого гідростатичного тиску, низькочастотної ультразвукової обробки, активного та модифікованого газового пакування, термічної обробки (мікрохвильова обробка, варіння, бланшування), а також культуральні, хроматографічні, спектрофотометричні та гравіметричні методи аналізу показників якості і безпечності сировини. Вплив високого гідростатичного тиску інтерпретовано як селективну інактивацію мікрофлори без вираженої денатурації білків. Було визначено, що рівень 300 МПа забезпечує санітарну стабілізацію охолодженої продукції, тоді як посилений режим 400 МПа × 5 хв для філе дорадо забезпечує зниження мезофільної аеробної мікрофлори до 3,2 log КУО/г зі збереженням текстурних властивостей. Для двостулкових молюсків технологічно значущим рівнем для повного відділення м'язів від панцира без будь-якого механічного втручання було 310 МПа. Були розраховані можливості інтенсифікації низькочастотним ультразвуком (25-40 кГц) для забезпечення контрольованої інтенсифікації кавітації та масообміну. Робоча частота 32,5 кГц та тривалість 15 хв забезпечили скорочення часу маринування рибного філе на 50-67 % без ознак структурного руйнування. Дослідження активної упаковки та модифікованої газової атмосфери виявило стабілізацію фізико-хімічних показників протягом 10 днів зберігання: вміст вологи 65,6-68,9 %, зниження pH до 6,59, водозв'язуюча здатність 71,74 %, що свідчить про збереження функціональної активності білкової матриці. Сушіння рибної сировини дозволило отримати білковий концентрат з вмістом вологи 9-10 % та масовою часткою білка до 66,7 %, коефіцієнт водозв'язуючої здатності 4,9 показав високий гідратаційний потенціал порошку. Мікрохвильова обробка забезпечила зниження мікрофлори до 3,5-4,2 log із кращим збереженням нутрієнтів. Суперкритична екстракція характеризувалася виходом ліпідів до 12-15 % та високою якістю екстракту. Результати можуть бути використані в м'ясо та рибопереробній промисловості для підвищення безпеки, стабільності та ефективності процесів переробки сировини

Ключові слова: санітарний стан; білкові фракції; процес ферментації; вологозв'язувальна здатність; частка білка