Information about the authors

Indira Temirova* – PhD candidate, Institute of Food Technology and Engineering, Saken Seifullin Kazakh Agrotechnical Research University, Republic of Kazakhstan; e-mail: indira_t85@mail.ru. ORCiD: https://orcid.org/0000-0002-9717-3236.

Gulnazym Ospankulova – PhD, Professor, Institute of Food Technology and Engineering, Saken Seifullin Kazakh Agrotechnical Research University, Republic of Kazakhstan; e-mail: bulashevag@gmail.com. ORCiD: https://orcid.org/0000-0002-6043-4658.

Aidyn Igenbayev – PhD, associate professor, Institute of Food Technology and Engineering, Saken Seifullin Kazakh Agrotechnical Research University, Republic of Kazakhstan; e-mail:aidyn_mamyt@mail.ru. ORCID: https://orcid.org/0000-0002-9903-2912.

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M. Sharapatova*, K. Issayeva
Toraighyrov University,
140000, Pavlodar, Republic of Kazakhstan, Pavlodar, Lomov Street, 64
*e-mail: madina_szd@mail.ru

RECENT ADVANCES IN THE TECHNOLOGICAL INTENSIFICATION OF ENZYMATIC PROCESSES IN MEAT SYSTEMS

Abstract: *Enzymatic reactions play a fundamental role in the transformation of muscle tissue into meat and in the formation of quality attributes in meat products. Postmortem glycolysis, proteolysis, and lipolysis mediated by endogenous enzymes – calpains, cathepsins, aminopeptidases, and lipases – determine texture, color, and flavor. Additional modification of the protein–lipid matrix is ensured by microbial enzymes of starter cultures and by exogenous plant-derived proteases used to regulate structural and sensory properties. Their activity promotes the accumulation of free amino acids, peptides, and volatile compounds responsible for characteristic flavor development. However, the natural rate of enzymatic reactions and the complexity of their control, influenced by pH, temperature, salt content, and water activity, require the application of controlled intensification strategies.*

This review summarizes current advances in innovative technologies aimed at accelerating and optimizing enzymatic processes in the meat industry. The effects of ultrasound (US), pulsed electric fields (PEF), moderate electric fields (MEF), high hydrostatic pressure (HHP), and supercritical CO_2 (SC-CO_2) are discussed in relation to protease activation, increased tissue permeability, and enzyme activity modulation. The review emphasizes that integrating non-enzymatic intensification methods with conventional fermentation and ripening technologies offers prospects for shortening production cycles, improving quality stability, and expanding the range of functional meat products. The findings provide a theoretical basis for the development of scientifically grounded modernization strategies in meat fermentation and ripening processes.

Key words: *enzymatic processes, meat industry, proteolysis, lipolysis, intensification.*

Introduction. Meat products occupy a significant position in human nutrition, serving as a major source of high-quality protein, essential amino acids, and micronutrients, while also providing distinctive sensory attributes that shape consumer perception of quality. Under conditions of intense market competition, the flavor profile of meat products is regarded as one of the key determinants of their commercial attractiveness and technological differentiation, thereby stimulating the search for scientifically grounded approaches to controlling texture and flavor development processes [1]. In this context, enzymatic mechanisms underlying the post-mortem transformation of muscle into meat play a pivotal role.

Enzymatic processes, through modification of the protein-lipid matrix, determine the structural-mechanical, sensory, and technological properties of meat products. Following slaughter, a cascade of interrelated biochemical reactions is initiated in muscle tissue, including glycolysis, proteolysis, and lipolysis, which are regulated by endogenous enzymatic systems. Anaerobic glycolysis is accompanied by the accumulation of lactic acid and a decline in pH, which induces the development of rigor mortis and significantly affects the ultrastructural organization of muscle fibers [2].

During the subsequent post-mortem period, calpains, cathepsins, and components of the ubiquitin-proteasome system play a central role in the selective degradation of myofibrillar and cytoskeletal proteins, leading to the development of tenderness and the accumulation of low-molecular-weight flavor-active compounds [3].

Concurrently, lipolytic enzymes catalyze the hydrolysis of triacylglycerols and phospholipids, generating precursors of volatile aroma compounds that contribute to the characteristic sensory profile of meat products.

In addition to endogenous enzymatic systems, exogenous plant-derived proteases are applied in meat processing to further intensify proteolysis through the hydrolysis of myofibrillar and, to some extent, connective tissue proteins. This approach enables targeted regulation of tenderization and acceleration of raw material maturation (Figure 1).

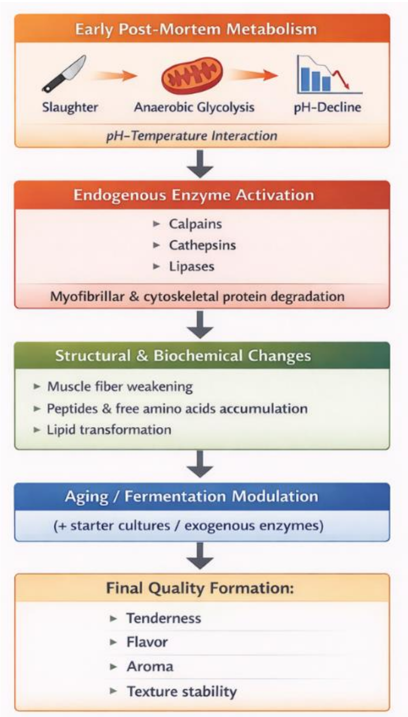

Figure 1 – Post-mortem biochemical cascade and quality formation in meat systems

In dry-cured and fermented meat technologies, endogenous enzymatic processes are substantially enhanced by microbial enzymes produced by starter cultures, as well as by yeasts and molds. The metabolic activity of these microorganisms intensifies proteolytic and lipolytic transformations, promoting the accumulation of free amino acids, low-molecular-weight peptides, and volatile compounds (e.g., aldehydes and ketones) responsible for the development of the product's characteristic flavor profile [2].

However, the rate of enzymatic reactions remains inherently limited and highly variable due to the sensitivity of enzyme systems to both intrinsic and extrinsic factors. These include temperature regimes, the dynamics of pH decline, sodium chloride concentration, water activity, and the physiological status of animals prior to slaughter, which determines muscle glycogen reserves and the subsequent extent of post-mortem acidification [4, 5].

The multifactorial nature of these processes complicates the standardization of technological parameters, reduces the reproducibility of quality attributes, and necessitates extended maturation times to achieve stable sensory and structural characteristics.

Contemporary development strategies in the meat industry focus on optimizing technological processes, including shortening maturation periods, improving quality reproducibility, and ensuring sensory consistency. In this context, particular attention has been directed toward approaches aimed at intensifying enzymatic reactions through the application of controlled physical factors.

In recent years, ultrasound, pulsed and moderate electric fields, high hydrostatic pressure, and supercritical carbon dioxide have been extensively investigated as tools for the targeted modulation of biochemical processes in muscle tissue [5, 6]. According to current research, these technologies can modify cell membrane permeability, induce the release of calcium-dependent proteases, alter the conformational state of enzymatic proteins, and enhance substrate availability for enzymatic interactions. Collectively, these effects contribute to the acceleration of proteolytic and lipolytic transformations while preserving nutritional value and microbiological safety.

The integration of physical intensification methods with conventional fermentation and aging strategies is therefore regarded as a promising direction for technological modernization in meat processing. Systematizing current knowledge on their mechanisms of action and their impact on the dynamics of proteolysis, lipolysis, and post-mortem structural modifications constitutes a necessary prerequisite for the development of scientifically grounded models for the controlled fermentation of meat products.

The objective of this review is to systematize contemporary technologies for the intensification of enzymatic processes in the meat industry, to analyze their molecular and biochemical mechanisms of action, and to evaluate their technological potential for industrial application.

Materials and methods. The present review is based on a systematic analysis of scientific publications addressing the intensification of enzymatic processes in the meat industry. Relevant sources were identified through searches conducted in the international bibliographic databases Scopus and Web of Science Core Collection. In addition, open-access search engines and academic electronic libraries were used to retrieve publications not indexed in the aforementioned databases. Statistical data from the Agency of Statistics of the Republic of Kazakhstan were used as supplementary reference information where relevant.

The systematic search was carried out using keywords and their combinations reflecting the scope of the study, including: enzymatic reactions, meat processing, process intensification, ultrasound, pulsed electric fields, moderate electric fields, high-pressure processing, supercritical CO_2, proteolysis, lipolysis, postmortem metabolism, and fermented meat products. The publication period was restricted to articles published between 1 January 2018 and 1 February 2026.

The initial screening of publications was performed through analysis of titles and abstracts to assess their relevance to the intensification of enzymatic processes in meat systems. The review included experimental and analytical studies focusing on the application of physical treatment methods influencing proteolysis, lipolysis, and post-mortem biochemical transformations. Publications not related to the meat industry or lacking sufficient scientific rigor were excluded from consideration.

Results and Discussion. Analysis of recent studies indicates that the intensity of post-mortem enzymatic transformations is primarily governed by the activity of endogenous proteases and lipases, as well as by technological processing conditions. In particular, the activity of the calpain system during the early post-mortem period has been shown to correlate with the rate of degradation of structural myofibrillar proteins, thereby determining meat texture and influencing its mechanical properties [7, 8].

These findings are further supported by experimental evidence demonstrating that variations in the kinetics of post-mortem pH decline and temperature regimes are associated with differences in calpain and cathepsin proteolytic activity. Consequently, heterogeneous modification of sarcoplasmic and myofibrillar proteins directly affects tissue toughness and the rate of structural relaxation [9]. Thus, the dynamics of post-mortem acidification play a decisive role in determining the extent of proteolytic modification and the degree of muscle fiber disintegration.

During subsequent aging, endogenous proteolytic mechanisms may be complemented by exogenous enzymes and microbial activity, which contribute to further degradation of connective tissue and muscle proteins. This synergistic action enhances tenderization and promotes the development of a more pronounced flavor profile.

In fermented meat products, endogenous post-mortem processes are augmented by microorganisms originating from the natural microbiota of raw meat and by deliberately inoculated starter cultures. The most commonly used microorganisms in the meat industry include lactic acid bacteria (e.g., Lactiplantibacillus plantarum, Lacticaseibacillus sakei, Pediococcus spp.), Gram-positive catalase-positive cocci (Staphylococcus carnosus, Staphylococcus xylosus), as well as yeasts and molds [10, 3].

Recent studies emphasize that microbial metabolites produced during lactic acid bacterial fermentation may exert pronounced antimicrobial activity and technological stabilization effects without the need to introduce viable cells. This approach is considered promising for the development of "clean-label" meat products [11, 2].

The potential of starter cultures in reduced-nitrite meat processing has also been demonstrated. In one study, the incorporation of a mixed culture of Limosilactobacillus fermentum and Staphylococcus carnosus enabled a reduction in sodium nitrite levels during meat curing without deterioration of technological or sensory properties [12]. The addition of approximately 10^7 CFU/g in combination with 50 mg/kg $NaNO_2$ resulted in a statistically significant decrease in residual nitrite and nitrate levels ($p < 0.05$), while simultaneously increasing nitrosyl pigment formation and improving redness compared with both reduced and standard nitrite treatments (100 mg/kg). Sensory and microbiological parameters remained comparable to control samples, supporting the feasibility of microbial cultures as partial substitutes for synthetic preservatives without compromising product quality and safety.

Alongside microbial mechanisms, alternative sources of exogenous proteases are actively explored to achieve more pronounced intensification of proteolysis. Among plant-derived enzymes, cysteine proteases such as papain (Carica papaya) [13], bromelain (Ananas comosus) [14, 15], and ficin (Ficus carica) [16] are widely applied due to their strong activity toward myofibrillar and connective tissue proteins. In experimental studies on beef steak, bromelain demonstrated a more controlled proteolytic effect and superior sensory performance compared to papain [14].

The mechanism of action of these plant enzymes involves nucleophilic attack by the thiolate group at the active site on peptide bonds, resulting in intensive hydrolysis of structural proteins, reduction of muscle toughness, and disruption of collagen fibers. However, their relatively low substrate specificity may lead to excessive degradation of the protein matrix and the development of a pasty texture when optimal dosages are exceeded. Moreover, excessive proteolysis has been shown to negatively affect water-holding capacity and structural integrity [17,18].

An additional limitation is the sensitivity of the thiol group in the active center to oxidation and thermal effects, which complicates the maintenance of a stable technological outcome.

To systematize the biological factors used for enzymatic process intensification in meat technology, Table 1 summarizes the principal groups of plant proteases and starter culture microorganisms, their mechanisms of action, and their technological effects.

Despite the potential of endogenous enzymatic systems, exogenously added proteases, and metabolically active starter cultures, the extent and direction of proteolytic and lipolytic transformations in meat systems largely depend on processing conditions. In this context, environmental parameters – including temperature, pH, water activity (aw), salt concentration, and aging regimes – act as key factors modulating enzyme activity, microbial viability, and substrate availability [19, 20].

An increase in temperature accelerates proteolysis and lipolysis; however, exceeding optimal levels may result in uncontrolled degradation of the protein matrix. Conversely, a reduction in water activity and changes in ionic strength limit enzyme mobility and substrate diffusion, thereby slowing biochemical reactions. Thus, technological parameters simultaneously function as regulatory tools and limiting factors of enzymatic transformations.

Consequently, there is a growing need to develop controlled intensification strategies capable of regulating the rate and direction of biochemical processes without compromising nutritional value or microbiological safety. In recent years, particular attention has been directed toward physical treatment methods capable of modifying the structure of the protein matrix and the activity of enzymatic systems in muscle tissue.

Table 1 – Plant-derived exogenous enzymes and starter culture microorganisms applied in meat technology

A)Plant proteases (exogenous enzymes)

Enzyme (source)	Class / Targets	Main Technological Effect	Risks / Limitations	References
Papain (Carica papaya)	Cysteine protease; myofibrillar and partially connective tissue proteins	Intensive proteolysis → tenderization and acceleration of aging; increased levels of low-molecular-weight peptides and free amino acids (FAAs)	Low substrate specificity → risk of pasty texture at excessive dosages; sensitivity of the –SH group to oxidation and thermal exposure	[17], [13]
Bromelain (Ananas comosus)	Pineapple-derived proteases; active against muscle proteins, elastin, and collagen (depending on conditions)	More controlled tenderization; improvement of juiciness, tenderness, and overall acceptability under optimized marination conditions	Excessive application may cause over-proteolysis and structural deterioration; activity strongly dependent on pH, temperature, and dosage	[18], [14], [15]
Ficin (Ficus carica)	Cysteine protease; muscle and matrix proteins	Mild tenderization and proteolysis; in formulations incorporating plant ingredients (e.g., fig powder) may improve the quality of fermented products	Careful optimization of dosage and treatment time required; activity varies depending on the product matrix	[16], [17]

(B) Starter Culture Microorganisms Used in Fermented and Dry-Cured Meat Products

Group / Species (examples)	Key Enzymatic Functions	Technological Effects (Quality / Safety)	Remarks on Processing Conditions (pH, aw, salt, temperature)	References
Lactic Acid Bacteria (LAB): Lactiplantibacillus plantarum, Latilactobacillus sakei, Limosilactobacillus fermentum, Pediococcus acidilactici, Latilactobacillus curvatus	Rapid acidification (↓pH); proteolysis/peptidolysis (contribution to FAAs); production of bacteriocins and organic acids	Biopreservation; inhibition of pathogens; fermentation stabilization; contribution to flavor and aroma via metabolic intermediates and precursors of volatile compounds	Strongly dependent on temperature, rate of pH decline, water activity (aw), and salt concentration; activity may be reduced under low aw or high salt conditions	[10], [3], [2]
Catalase-positive cocci (CNS): Staphylococcus carnosus, S. xylosus, (occasionally Kocuria varians)	Nitrite reductase activity (color formation/stabilization); catalase (↓oxidation); lipolysis and proteolysis (aroma development)	Improvement of color stability; enhancement of aromatic profile via secondary metabolites; reduction of oxidative defects; technological compatibility with LAB	Require controlled salt concentration and temperature; sensitive to aggressive curing/aging regimes	[12], [3]
Yeasts: Debaryomyces hansenii (commonly used in dry-cured products)	Proteolysis/peptidolysis; contribution to volatile compound formation; lactate utilization; surface stabilization	Enhancement of aroma; reduction of surface defects; gradual moderation of excessive acidity	Strongly dependent on aw and salt; surface aeration is essential	[3]
Molds: Penicillium nalgiovense (surface inoculation)	Surface enzymes (proteases/lipases); antioxidant and barrier effects; competitive inhibition of undesirable microflora	Stabilization of ripening; development of aged flavor; surface protection	Requires controlled humidity and aeration; risk of defects under improper environmental control	[5]

Ultrasound (US)

Ultrasound treatment is considered one of the most promising physical methods for intensifying biochemical processes in the meat industry. Its mechanism of action is based on acoustic cavitation generated during the propagation of low-frequency waves (20-100 kHz) in a liquid medium. During alternating compression and rarefaction cycles, cavitation bubbles are formed; their growth and collapse generate localized extreme temperatures and pressures, shock waves, and microjets, resulting in pronounced mechanical and physicochemical effects on muscle tissue structure [21]. The combined cavitational, mechanical, and localized thermal effects constitute the basis for targeted microstructural modification, enhanced diffusion phenomena, and activation of enzymatic systems.

Within technologically relevant parameter ranges, ultrasound is capable of disrupting the ultrastructure of muscle fibers and increasing the permeability of cellular and lysosomal membranes, thereby facilitating the release of intracellular enzymes and substrates [22]. Cavitation has been shown to modulate endogenous protease activity through multiple mechanisms. For example, ultrasound treatment of salted pork resulted in pronounced myofibrillar fragmentation and lysosomal disruption, leading to increased release of cathepsins B and L and accelerated proteolysis [23].

Similarly, peptidomic analyses of ultrasound-treated bacon revealed increased concentrations of low-molecular-weight peptides and flavor-active compounds [25]. Additional studies confirmed enhanced degradation of myofibrillar and sarcoplasmic proteins following ultrasound application, accompanied by elevated levels of free amino acids (e.g., Glu, Ala, Thr) and oligopeptides [25, 26].

Ultrasound-induced cavitation also increases membrane permeability and promotes extracellular Ca^{2+} influx, thereby facilitating activation of μ- and m-calpains. It has been demonstrated that elevated intracellular Ca^{2+} levels following ultrasound exposure stimulate the calpain system and accelerate hydrolysis of structural proteins such as actin and myosin, ultimately improving textural properties [27]. Thus, ultrasound intensifies proteolysis via both lysosome-dependent and calcium-dependent pathways, involving cathepsin and calpain enzyme systems.

In contrast to conventional technologies primarily relying on thermal treatment and microbial fermentation, ultrasound operates through cavitational, mechanical, and localized thermal effects, enabling more rapid and precise modulation of biochemical processes [24]. When parameters are optimized, ultrasound accelerates flavor development with reduced dependence on prolonged aging, while preserving nutritional and sensory attributes.

Beyond its effect on endogenous enzymes, ultrasound enhances the efficiency of exogenous proteases. Cavitation-induced disruption of Z-lines and collagen structures in the bovine longissimus lumborum muscle has been shown to facilitate papain penetration into deeper tissue layers and to accelerate the formation of low-molecular-weight peptides [28]. Furthermore, ultrasound has been reported to induce peptide chain unfolding and increase substrate accessibility, thereby enhancing the release of flavor-active amino acids (e.g., Asp, Glu) [29]. This synergistic effect is attributed to improved mass transfer and increased exposure of protein active sites.

Ultrasound may also influence lipolytic processes. Disruption of membrane structures and modification of the substrate microenvironment enhance lipase access to triacylglycerols and phospholipids, potentially intensifying lipolysis and the formation of aroma precursors [30]. Consequently, ultrasound is capable of modulating both proteolytic and lipolytic pathways, exerting a comprehensive effect on the development of the flavor profile.

Consequently, ultrasound is capable of modulating both proteolytic and lipolytic transformations, thereby exerting a comprehensive influence on flavor development. The practical relevance of this mechanism becomes particularly significant in the processing of meats characterized by a pronounced specific aroma, where the controlled formation and transformation of volatile compounds are critical determinants of consumer acceptability. In the context of lamb processing – widely represented in the structure of red meat consumption in the Republic of Kazakhstan – ultrasound may be regarded as a tool for targeted modification of lipid and protein fractions involved in the formation of the characteristic ovine aroma. Controlled intensification of lipolysis and subsequent transformation of free fatty acids may potentially regulate the balance of aroma precursors, reducing the intensity of undesirable sensory notes while preserving the traditional qualities and cultural identity of the product.

Despite its demonstrated efficacy, excessive ultrasound intensity may promote lipid and protein oxidation, reduce the stability of volatile compounds, and generate variability in textural attributes due to localized extreme cavitation effects.

Practical limitations include the relatively high energy demand of the process; as stable cavitation requires high-power equipment. A portion of acoustic energy dissipates as heat, resulting in localized temperature increases and necessitating additional thermal control, thereby increasing total energy consumption within the production line [22].

Scale-up from laboratory to industrial applications presents additional challenges. Non-uniform distribution of the ultrasonic field in bulk material – particularly in large muscle cuts – often requires multi-probe or flow-through system configurations [21], increasing both energy consumption and capital investment. Moreover, the absence of universal processing regimes for different meat types complicates standardization and necessitates further optimization considering tissue morphology and physicochemical characteristics.

Overall, further advancement of ultrasound technology in meat processing requires parameter optimization, deeper investigation of molecular mechanisms, and the development of energy-efficient industrial systems that ensure process controllability, reproducibility, and sensory stability.

High-Pressure Processing (HPP)

High-Pressure Processing (HPP) is a non-thermal technology based on the application of uniform isostatic hydrostatic pressure in the range of 300-700 MPa for short durations (seconds to minutes), typically using water as the pressure-transmitting medium [31].

A major advantage of HPP is the ability to perform treatment at ambient or reduced temperatures, thereby preserving the sensory and nutritional characteristics of meat products. In contrast to ultrasound, HPP is not associated with cavitation phenomena; instead, its effects result from the uniform transmission of pressure throughout the product according to Pascal’s principle. The primary effects include denaturation of membrane proteins, disruption of membrane integrity, increased cellular permeability, conformational modifications of proteins, and inactivation of certain enzymes and vegetative microorganisms [32]. For this reason, HPP has traditionally been applied as a cold pasteurization technology. However, increasing attention has recently been directed toward its potential to modulate enzymatic processes in meat systems.

The influence of HPP on enzymatic systems strongly depends on processing parameters such as pressure level, temperature, and treatment time. At moderate pressure levels, stimulation of certain enzymatic reactions may occur, whereas higher pressures often lead to enzyme denaturation. For example, moderate pressure treatment (130 MPa at 10 °C) has been shown to promote metmyoglobin reduction through activation of the enzymatic redox system, thereby enhancing meat redness [32]. However, increasing pressure beyond optimal levels resulted in impaired enzymatic activity.

It has also been reported that treatment at 600 MPa for 6 minutes in dry-cured ham increased lipid oxidation intensity while reducing aminopeptidase activity, suggesting partial enzyme denaturation at high pressures [33]. Thus, depending on processing intensity, HPP may either modulate or suppress proteolytic and lipolytic reactions.

The effect of HPP on meat tenderness is associated with pressure-induced enzyme release at specific pressure levels, followed by maintenance of enzymatic activity during subsequent holding under controlled time–temperature conditions [34]. Combined application of papain and HPP has been shown to significantly reduce shear force and enhance meat tenderization [35].

In addition, HPP can be applied to improve lower-value cuts by inducing structural modification of muscle tissue and enhancing gel formation in processed meat products. This contributes to the development of stable protein matrices with improved water- and fat-holding capacity [34].

Considering the high consumption of red meat (beef, lamb, and horse meat) in Kazakhstan [36], along with the extensive use of cuts containing high levels of connective tissue, increasing the consumer value of tougher and less demanded carcass portions represents an important technological objective. In this context, HPP can be regarded as a value-added processing tool, enabling targeted reduction of shear force and formation of stable protein structures in minced and restructured products, thereby improving water and fat retention, processing yield, and textural uniformity [33].

Despite its technological potential, HPP applications in this field remain limited at the industrial scale due to technical complexity and the need for substantial adaptation of production lines. The labile nature of muscle proteins makes fresh tissue highly sensitive to pressure – temperature-time combinations. Depending on processing parameters, undesirable changes in appearance, color, and texture may occur, thereby restricting broader industrial adoption [37]. Furthermore, elevated pressures may accelerate lipid oxidation and inactivate beneficial enzymatic systems.

Overall, High-Pressure Processing represents a powerful tool for controlled modulation of protein and enzymatic systems in meat tissue. Unlike ultrasound, which primarily acts through localized mechanical disruption and enzyme activation, HPP exerts isotropic conformational effects on molecular structures, resulting in either enhancement or suppression of enzymatic reactions depending on the selected processing regime. The technological promise of HPP lies in its capacity to enable controlled modulation of proteolysis, color formation, and texture development, provided that parameters are carefully optimized and the process is effectively adapted for industrial implementation.

Electrical Stimulation (ES)

Electrical Stimulation (ES) is a post-mortem technology based on the application of electrical impulses to carcasses in order to accelerate biochemical processes and improve meat quality attributes. At the industrial scale, high-voltage electrical stimulation (HVES; 450-3600 V) is widely applied to enhance tenderness and improve the technological properties of beef and lamb [38].

High-voltage electrical stimulation induces intensive muscle contractions during the early post-mortem period, leading to accelerated ATP depletion, activation of glycolysis, and a more rapid decline in pH. As a result, rigor mortis develops at a relatively higher muscle temperature, reducing the risk of cold shortening and contributing to improved tenderness.

A key biochemical effect of ES is the enhanced release of Ca^{2+} from the sarcoplasmic reticulum due to electrically induced muscle contractions. This process activates the calpain system and accelerates proteolytic degradation of myofibrillar proteins [38]. In contrast to ultrasound treatment – where increased Ca^{2+} levels are primarily associated with enhanced membrane permeability and mechanical disruption of intracellular structures – electrical stimulation triggers a physiologically mediated release of calcium ions characteristic of muscle contraction [39]. Thus, calpain activation during ES occurs within the framework of the muscle’s natural contraction mechanism.

The effect of pulsed electric fields (PEF; 2.5-10 kV; 50-90 Hz) on the Longissimus dorsi muscle during a 21-day aging period has also been investigated [40]. A moderate increase in calpain activity and enhanced proteolysis of Troponin-T were observed, indicating the potential of PEF to accelerate tenderization; however, no pronounced effect on shear force was detected.

Other authors [41] demonstrated that treatment of lamb with electric pulses (1-1.4 kV/cm) was associated with increased levels of free amino acids and enhanced release of cathepsins, suggesting stimulation of enzymatic processes. Simultaneously, a reduction in fatty acid content was observed, attributed to intensified lipid oxidation. Therefore, the effectiveness of PEF depends on field strength and the stage of post-mortem aging.

Moderate Electric Fields (MEF; 1-1000 V/cm; 50-25,000 Hz) represent a technology combining membrane electroporation with controlled ohmic heating generated by alternating current passing through biological tissue [42]. In contrast to high-energy pulsed regimes, MEF provides a milder yet controlled impact on muscle structure.

Application of MEF is accompanied by increased membrane permeability, accelerated post-mortem glycolysis, and a faster decline in pH (to values below 6.0 before muscle temperature reaches approximately 10°C), thereby optimizing early post-mortem processes [39]. In addition, electroporation induces intracellular Ca^{2+} release, activating calpains and enhancing proteolytic degradation of myofibrillar proteins during aging [36].

From a technological perspective, the combined application of electrical stimulation, PEF, and MEF contributes to accelerated pH decline, reduced risk of cold shortening, intensified proteolysis, improved tenderness, and shortened aging time. However, the magnitude of these effects critically depends on field strength, frequency, temperature, and treatment duration. Under uncontrolled conditions, excessive pH decline, intensified oxidative reactions, and deterioration of color characteristics may occur, limiting the universality of the technology and necessitating strict optimization of processing parameters.

Supercritical Fluids (SC-CO_2)

Supercritical fluids, predominantly supercritical carbon dioxide (SC-CO_2), represent a technology based on the use of CO_2 above its critical parameters (Pc = 73.8 bar; Tc = 31.1 °C). In this state, the substance exhibits combined properties of a gas (high diffusivity) and a liquid (solvent capacity), enabling intensive mass transfer and selective interaction with biological matrices [43]. Although the primary application of SC-CO_2 in the food industry has traditionally been the extraction of target compounds, increasing attention is being directed toward its potential for modification of meat systems, including lipid, microbial, and structural components.

Of particular relevance to the meat sector are studies investigating the use of SC-CO_2 for lipid extraction. Research has demonstrated that supercritical CO_2 effectively extracts lipids from pork and lamb tissues [44]. Owing to its selective solubility toward nonpolar compounds, the technology may be applied for controlled defatting of meat raw materials, partial modification of lipid profiles, and recovery of functional lipid fractions. Additionally, SC-CO_2 has been used for the extraction of trace amounts of antibiotics from meat matrices [43], highlighting its potential in food safety and quality control. These findings indicate that the technology can efficiently penetrate dense muscle tissue and interact with intramuscular components without causing pronounced thermal degradation of structural integrity.

Particular practical interest lies in studies exploring the combined application of SC-CO_2 with other physical methods. In the same study [45], SC-CO_2 in combination with ultrasound and physiological saline was applied for the inactivation of Escherichia coli in dry-cured ham. Effective microbial decontamination was achieved without significant alterations in color, texture, or pH. This result is particularly important, as it demonstrates the possibility of mild non-thermal stabilization of meat products while preserving sensory characteristics.

Other authors [46] investigated a combined ultrasound and SC-CO_2 technology during drying of chicken breast. The integrated approach achieved inactivation of mesophilic microbiota, yeasts, molds, and Salmonella spp., while preserving protein nutritional value and minimizing thermal tissue damage. Thus, SC-CO_2, particularly when integrated with complementary technologies, functions as a tool for controlled microbial stabilization and structural modification of meat systems. Due to its high solubility in the aqueous phase of muscle tissue and its ability to form carbonic acid, SC-CO_2 can alter the microenvironment of the protein-lipid matrix, affect membrane permeability, and influence the kinetics of enzymatic reactions.

Industrial implementation of supercritical CO_2 in meat processing remains limited by high equipment costs and the requirement for operation under elevated pressures, which complicate process scale-up and increase energy consumption [39]. Furthermore, the limited number of studies specifically addressing the impact of SC-CO_2 on muscle enzymatic systems, as well as the potential for enzyme inactivation under extreme processing conditions, indicate the need for further parameter optimization and deeper investigation of the molecular mechanisms underlying SC-CO_2 interaction with the meat matrix.

Overall, comparison of the discussed technologies highlights fundamental differences in their mechanisms of action on the protein and lipid matrix of muscle tissue. A comparative analysis of these physical methods is presented in Table 2.

The presented data indicate that the selection of an intensification method should be based on the targeted technological outcome and the morpho-functional characteristics of the processed raw material.

The application of starter cultures (LAB, Staphylococcus spp., yeasts/molds) and/or exogenous plant-derived proteases, as well as the integration of physical intensification methods (US, HPP, PEF/MEF, SC-CO_2), expands the possibilities for targeted modulation of membrane permeability, activation of Ca^{2+}-dependent proteases, and alteration of protein conformational states. Collectively, these approaches enhance quality reproducibility and enable shortening of maturation time while maintaining sensory acceptability.

Nevertheless, large-scale industrial implementation remains constrained by technological and economic factors, including high capital investment requirements (particularly for HPP and SC-CO_2), energy consumption, operational safety considerations associated with high pressures and voltages, and the risk of undesirable effects under improperly optimized conditions (e.g., intensified lipid oxidation, color instability, excessive proteolysis, and loss of structural integrity in the case of plant proteases).

Table 2 – Comparative mechanisms of action of physical methods for the intensification of enzymatic processes in meat systems

Method	Cellular / Structural Effect	Enzymatic Effect	Technological Outcome	References
Ultrasound (US)	Cavitation, shock waves, microstreaming; increased permeability of cellular and lysosomal membranes; enhanced diffusion	↑ Release of cathepsins B/L (lysosomal); ↑ Ca^{2+} influx and activation of μ- and m-calpains; intensified proteolysis and accumulation of peptides and FAA	↑ Tenderness; ↑ flavor-active peptides and FAA; accelerated development of flavor profile; enhanced efficacy of exogenous proteases	[21], [22], [23], [26], [29]
High-Pressure Processing (HPP)	Isotropic pressure (300-700 MPa); protein conformational changes; membrane disruption; altered membrane permeability	Modulation of enzymatic activity: under moderate regimes, activation of specific systems possible (e.g., MetMb reduction); under high pressures, enzyme inactivation (e.g., aminopeptidases) and increased oxidative reactions	"Cold pasteurization"; effects on color/redness; texture modification; controlled structuring/gelation; tenderization potential for low-value cuts	[31], [32], [33], [34]
Electrical Stimulation (HVES / PEF / MEF)	HVES: intensive contractions, accelerated glycolysis and pH decline; PEF/MEF: membrane electroporation; MEF additionally induces ohmic heating	↑ Ca^{2+} release and calpain activation; accelerated proteolysis of myofibrillar proteins; under PEF, possible release of cathepsins (regime- and aging stage-dependent)	↓ Risk of cold shortening; accelerated aging; ↑ tenderness; effect critically depends on processing parameters (voltage/frequency/temperature/time)	[38], [39], [40], [41]
Supercritical CO_2 (SC-CO_2)	High diffusivity and selective interaction; extraction of lipids and microcomponents; when combined with US – enhanced mass transfer and microbial destabilization	Direct evidence on muscle enzymatic systems remains limited; technologically relevant effects include extraction and microbial inactivation (especially in combination with US)	Lipid/fraction extraction; reduction of undesirable trace components; microbial inactivation while preserving color/texture/pH (under combined regimes)	[43], [44], [45]

In this regard, the most promising practical trajectory lies in combined, selectively applied solutions – particularly for premium products, clean-label segments, food safety enhancement, shelf-life extension, or processing of low-value cuts – accompanied by strict parameter standardization (P–T–t; E–f–t; ultrasound intensity; aw/NaCl/pH) and mandatory validation for specific raw materials and processing schemes.

Under the conditions of Kazakhstan, the applied relevance of such approaches is further strengthened by the structure of the raw material base and consumption patterns. The high proportion of red meat (beef, lamb, horse meat) and the extensive utilization of cuts with elevated connective tissue content generate demand for solutions that improve tenderness, water-holding capacity, and technological yield without compromising traditional product identity. In this context, controlled intensification of proteolysis and the formation of more stable protein matrices – particularly through HPP and combined schemes involving ultrasound, electric fields, and starter cultures – may serve as a pathway for increasing the added value of tougher cuts and developing product lines with more predictable sensory profiles.

An additional prerequisite for market acceptance of these technologies is appropriate communication of their benefits. Labeling and informational elements should translate technological terminology into consumer-relevant advantages (e.g., safety, quality stability, reduced nitrite/additive levels, reproducible flavor and texture), thereby mitigating skepticism toward non-thermal processing technologies.

Conclusion. The quality of meat products is determined by the multifactorial interaction of post-mortem glycolysis, proteolysis, and lipolysis with technological processing parameters that regulate the rate and direction of biochemical transformations within the protein-lipid matrix. The synthesized evidence indicates that the combination of biotechnological tools (starter cultures, microbial metabolites/postbiotics, exogenous enzymes) with physical intensification methods (ultrasound, electric fields, high-pressure processing, and supercritical CO_2) provides a scientifically grounded framework for the controlled acceleration of aging and the targeted formation of desirable sensory and textural attributes while ensuring microbiological safety. The practical potential of these approaches lies in improving quality reproducibility and technological stability. However, their broader industrial implementation requires careful optimization of processing regimes, thorough assessment of risks associated with oxidative and structural defects, and the development of standardized protocols tailored to specific raw materials and product categories.

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М.М. Шарапатова*, К.С. Исаева
Торайғыров университеті,
140000, Павлодар, Қазақстан Республикасы, Павлодар қ., Ломов к-сі, 64
*e-mail: madina_szd@mail.ru

ЕТ ӨНЕРКӘСІБІНДЕ ФЕРМЕНТАТИВТІК ПРОЦЕССТЕРДІ ИНТЕНСЕФИКАЦИЯЛАУДЫҢ ЗАМАНАУИ ТЕХНОЛОГИЯЛАРЫ

Ферментативтік реакциялар бұлшықетінің етке трансформациялануында және ет өнімдерінің сапа көрсеткіштерінің қалыптасуында шешуші рөл атқарады. Постмортем кезеңінде жүретін гликолиз, протеолиз және липолиз үдерістері эндогенді ферменттер – кальпаиндер, катепсиндер, аминопептидазалар мен липазалар – әсерімен жүзеге асырылып, өнімнің құрылымдық, түс және дәм мен хош иістік сипаттамаларын айқындайды. Ақуыз-липидтік матрикстің қосымша модификациясы старттық культуралармен, сондай-ақ құрылымдық және сенсорлық қасиеттерді реттеу мақсатында қолданылатын өсімдіктекті экзогенді протеазалар арқылы қамтамасыз етіледі. Олардың белсенділігі еркін аминқышқылдарының, пептидтердің және өнімнің өзіндік дәмі мен хош иісін қалыптастыратын ұшқыш қосылыстардың жинақталуына ықпал етеді. Алайда ферментативтік реакциялардың табиғи жылдамдығы және олардың pH, температура, тұз мөлшері мен су белсенділігіне тәуелді күрделі реттелуі басқарылатын интенсификациялау әдістерін қолдануды талап етеді.

Ғылыми шолуда ет өнеркәсібінде ферментативтік үдерістерді жеделдетуге және оңтайландыруға бағытталған инновациялық технологиялар саласындағы заманауи ғылыми жетістіктер жүйеленген. Ультрадыбыстың (US), импульстік (PEF) және орташа электр өрістерінің (MEF), жоғары гидростатикалық қысымның (HHP), сондай-ақ аса критикалық көмірқышқыл газының (SC-CO_2) протеазаларды белсендіру, тіндердің өткізгіштігін арттыру және ферменттік белсенділікті реттеу тұрғысындағы әсері қарастырылады. Ферментативтік емес интенсификациялау әдістерін дәстүрлі ферментация және жетілдіру технологияларымен ықпалдастыру өндірістік циклдің қысқаруына, сапаның тұрақтылығының артуына және функционалдық ет өнімдері ассортиментінің кеңеюіне мүмкіндік беретіні айқындалады. Ұсынылған *тұжырымдар ет өнеркәсібіндегі ферментация және жетілдіру үдерістерін жаңғыртуға арналған ғылыми негізделген бағдарламаларды әзірлеудің теориялық негізін қалыптастырады.*

Түйін сөздер: *ферментативтік үдерістер, ет өнеркәсібі, протеолиз, липолиз, интенсификациялау.*

М.М. Шарапатова*, К. Исаева
Торайгыров университет,
140000, Павлодар, Республика Казахстан, г. Павлодар, ул. Ломова, 64
*e-mail: madina_szd@mail.ru

СОВРЕМЕННЫЕ ТЕХНОЛОГИИ ИНТЕНСИФИКАЦИИ ФЕРМЕНТАТИВНЫХ ПРОЦЕССОВ В МЯСНОЙ ПРОМЫШЛЕННОСТИ

Ферментативные реакции играют ключевую роль в трансформации мышечной ткани в мясо и формировании показателей качества мясных продуктов. Постмортемные процессы гликолиза, протеолиза и липолиза, опосредованные действием эндогенных ферментов – кальпаинов, катепсинов, аминопептидаз и липаз, определяют текстуру, цвет и вкусо-ароматические характеристики продукции. Дополнительная модификация белково-липидного матрикса обеспечивается ферментами стартовых культур, а также экзогенными протеазами растительного происхождения, применяемыми для регулирования структурных и сенсорных свойств. Их активность способствует накоплению свободных аминокислот, пептидов и летучих соединений, формирующих характерный профиль вкуса и аромата. Однако естественная скорость ферментативных реакций и сложность их контроля, обусловленные влиянием pH, температуры, содержания соли и водной активности, требуют применения методов управляемой интенсификации.

В обзоре обобщены современные достижения в области инновационных технологий, направленных на ускорение и оптимизацию ферментативных процессов в мясной промышленности. Рассматривается влияние ультразвука (US), импульсных (PEF) и умеренных электрических полей (MEF), высокогидростатического давления (HHP) и сверхкритического CO_2 *(SC-*CO_2*) на активацию протеаз, повышение проницаемости тканей и модуляцию ферментативной активности. Подчёркивается, что интеграция неферментативных методов интенсификации с традиционными технологиями ферментации и созревания открывает возможности сокращения производственного цикла, повышения стабильности качества и расширения ассортимента функциональных мясных продуктов. Представленные обобщения формируют теоретическую основу для разработки научно обоснованных программ модернизации процессов ферментации и созревания в мясной промышленности.*

Ключевые слова: *ферментативные процессы, мясная промышленность, протеолиз, липолиз, интенсификация.*

Information about the authors

Madina Sharapatova* – corresponding author, doctoral student of the Department of Biotechnology, Toraighyrov University, Pavlodar, Kazakhstan; e-mail: madina_szd@mail.ru. ORCID: https://orcid.org/0009-0009-1094-8579.

Kuralay Issayeva – Candidate of Technical Sciences, Associate Professor of the Department of Biotechnology, Toraighyrov University, Pavlodar, Kazakhstan; e-mail: issayevakuralay@mail.ru. ORCID: https://orcid.org/0000-0003-4533-0188.

Авторлар туралы мәліметтер

Мадина Мадениетовна Шарапатова* – «Биотехнологии» кафедрасының докторанты, Павлодар қаласының Торайғыров Университеті, Қазақстан Республикасы; e-mail: madina_szd@mail.ru. ORCID: https://orcid.org/0009-0009-1094-8579.

Куралай Сметкановна Исаева – техника ғылымдарының кандидаты, «Биотехнология» кафедрасының қауымдастырылған профессоры, Павлодар қаласының Торайғыров Университеті, Қазақстан Республикасы; e-mail: issayevakuralay@mail.ru. ORCID: https://orcid.org/0000-0003-4533-0188.

Сведения об авторах

Мадина Мадениетовна Шарапатова* – докторант кафедры «Биотехнологии», Торайгыров Университет города Павлодар, Республика Казахстан; e-mail: madina_szd@mail.ru. ORCID: https://orcid.org/0009-0009-1094-8579.

Куралай Сметкановна Исаева – кандидат технических наук, ассоциированный профессор кафедры «Биотехнологии», Торайгыров Университет города Павлодар, Республика Казахстан; e-mail: issayevakuralay@mail.ru. ORCID: https://orcid.org/0000-0003-4533-0188.

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А.К. Мустафаева[1*], Р. Асқар[1], Ш. Сәкен[1], Е.Б. Муталиев[1], Г.Б. Абдилова[2]
[1]Сәкен Сейфуллин атындағы Қазақ агротехникалық зерттеу университеті,
010011, Қазақстан Республикасы, Астана қаласы, Жеңіс даңғылы 62
[2]Шәкәрім университеті,
071412, Қазақстан Республикасы, Семей қ., Глинка к-сі, 20 А
*e-mail: ayaulym.mustafa@mail.ru

ҰЛТТЫҚ СҮТҚЫШҚЫЛДЫ ӨНІМ ӨНДІРУ ТЕХНОЛОГИЯСЫ

Аңдатпа: *Бұл ғылыми жұмыста түйе сүтінің биохимиялық және технологиялық артықшылықтарын ескере отырып, кептірілген өрік қосылған ұлттық құрт өнімін өндіру технологиясы әзірленді. Зерттеу барысында түйе сүтінің физика-химиялық қасиеттері, оның ашытуға қолайлы табиғи параметрлері және құрт дайындау тиімділігі талданды. Кептірілген өріктің тағамдық және функционалдық қасиеттері анықталады, атап айтқанда табиғи қант, калий, β-каротин және пектиндер құрттың сапалық көрсеткіштерін арттыру үшін қолданылды.*

Зерттеу жұмысы дайын өнімнің химиялық құрамын, органолептикалық белгілерін, ылғалдылығын, қышқылдылығын, дәрумендік құрамын және энергетикалық құндылығын анықтауды қамтиды. 3%, 5%, 7% кептірілген өрік қосылған үлгілер салыстырмалы түрде зерттелді. Олардың ішінен 5% кептірілген өрікті нұсқа дәмдік, құрылымдық және дәрумендік құрам бойынша ең тиімді деп танылды. Таңдап алынған үлгідегі В тобының дәрумендік тобы төмендегідей нәтиже көрсетті: B_1-0,057±0,011, B_2-0,208±0,085, B_3-4,22±0,818, B_5-0,330±0,064, B_6-0,125±0,023.

Ғылыми жұмыс нәтижесінде кептірілген өрік қосылған түйе сүтінен құрт өндірудің ғылыми негізделген технологиялық сұлбасы ұсынылып, өнімнің тағамдық құндылығы мен функционалды қасиеттерін арттыру мүмкіндігі дәлелденді. Бұл технология ұлттық өнімдерді жаңғыртуға және олардың нарықтағы сұранысын кеңейтуге мүмкіндік береді.

Түйін сөздер: *түйе сүті, сиыр сүті, ұлттық сүтқышқылды өнім, құрт, кептірілген өрік.*

Кіріспе

Тамақ өнімдерін өндіру саласында соңғы жылдары функционалды бағыттағы ұлттық тағамдарды ғылыми тұрғыдан жаңғырту мен олардың тағамдық қасиеттерін арттыру мәселесі өзекті зерттеу нысанына айналып отыр [1]. Бұл үрдіс халықтың табиғи, биологиялық белсенді, қауіпсіз және жоғары құнарлы өнімдерге деген сұранысының артуымен, сондай-ақ дәстүрлі тағамдарды жаңа технологиялық тәсілдер арқылы жетілдіру қажеттілігімен түсіндіріледі. Осы бағытта сүт туынды өнімдерін, әсіресе ұлттық тағамдар қатарын кеңейтуге мүмкіндік беретін технологиялық шешімдерді әзірлеу – қазіргі тағамтану ғылымының маңызды міндеттерінің бірі.

Қазақстанның табиғи – климаттық жағдайы түйе шаруашылығын дамытуға өте қолайлы, әсіресе шөл және шөлейт аймақтарда түйе сүті негізгі ауылшаруашылық шикізаттарының біріне айналған. Елдегі түйе басы санының тұрақты өсуі түйе сүтін өнеркәсіптік өңдеу технологияларын жетілдіруді және оның негізінде ұлттық әрі функционалдық өнімдер ассортиментін арттыруды талап етеді [2].

Түйе сүті – химиялық құрамының ерекшелігімен және биологиялық белсенділігінің жоғарылығымен танылған табиғи өнім. Оның құрамында жеңіл сіңетін ақуыздар, иммундық қасиеті күшті лактопероксидаза жүйесі, темір, С дәрумені және қанықпаған май қышқылдары мол.