ANIMAL SCIENCE AND FOOD TECHNOLOGY

Founder:
National University of Life and Environmental Sciences of Ukraine

Year of foundation: 2010

Recommended for printing and distribution
via the Internet by the Academic Council
of National University of Life and Environmental Sciences of Ukraine
(Minutes No. 11 of May 22, 2025)

Decision of the National Council of Television and Radio Broadcasting of Ukraine
No. 1721, Minutes No. 30, dated 11.12.2023
Media identifier – R30-02314**.**

The journal is included in the list
of Professional Scientific Publications of Ukraine
Category "A". Branch of sciences: Agricultural. Specialty: 0721 – Food processing,
0811 – Crop and livestock production, 0831 – Fisheries.
(order of the Ministry of Education and Science of Ukraine
of February 24, 2025, No. 349)

The journal is presented international scientometric databases, repositories and scientific systems: Scopus, Google Scholar, Vernadsky National Library of Ukraine, BASE, AGRIS, Directory of Open Access Journals (DOAJ), Ulrichsweb, Dimensions, University of Oslo Library, University of Hull Library, SOLO – Search Oxford Libraries Online, European University Institute, Leipzig University Library, Cambridge University Library, UCSB Library, OUCI (Open Ukrainian Citation Index), WorldCat, EuroPub, Professional publications of Ukraine, CORE, EBSCO, Litmaps, Cosmos Impact Factor

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ТВАРИННИЦТВО ТА ТЕХНОЛОГІЇ ХАРЧОВИХ ПРОДУКТІВ

Засновник:
Національний університет біоресурсів і природокористування України

Рік заснування: 2010

Рекомендовано до друку та поширення
через мережу Інтернет Вченою радою
Національного університету біоресурсів і природокористування України
(протокол № 11 від 22 травня 2025 р.)

Рішення Національної Ради України з питань телебачення і радіомовлення
№ 1721, протокол № 30 від 11.12.2023 р.
Ідентифікатор медіа – R30-02314.

Журнал входить до переліку
наукових фахових видань України

Категорія «А». Галузь знань: Сільськогосподарські науки,
спеціальності – 181 «Харчові технології»,
204 «Технологія виробництва і переробки продукції тваринництва»,
207 «Водні біоресурси та аквакультура»
(Наказ Міністерства освіти і науки України від 24 лютого 2025 р. № 349)

Журнал представлено у міжнародних наукометричних базах даних, репозитаріях та пошукових системах: Scopus, Google Scholar, Національна бібліотека України імені В. І. Вернадського, BASE, AGRIS, Directory of Open Access Journals (DOAJ), Ulrichsweb, Dimensions, University of Oslo Library, University of Hull Library, SOLO – Search Oxford Libraries Online, European University Institute, Leipzig University Library, Cambridge University Library, UCSB Library, OUCI (Open Ukrainian Citation Index), WorldCat, EuroPub, Фахові видання України, CORE, EBSCO, Litmaps, Cosmos Impact Factor

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Journal homepage: https://animalscience.com.ua/en
Animal Science and Food Technology, 16(2), 9-22
Received 01.02.2025 Revised 17.04.2025 Accepted 22.05.2025

UDC 636.5.086:582.794.1]:582.794.1
DOI: 10.31548/animal.2.2025.09

The effectiveness of using fennel meal (*Foeniculum vulgare*) in feeding young quails

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Abstract. Fennel seeds are considered a potent phytobiotic and can be used in the feeding of young poultry as an alternative to antibiotics, which are applied to improve poultry performance and prevent a range of gastrointestinal diseases. The conducted scientific and economic study focused on examining the impact of feeding fennel seed cake on the performance and slaughter

Suggested Citation:
Kholiavska, T., Umanets, D., Tytariova, O., & Umanets, R. (2025). The effectiveness of using fennel meal (*Foeniculum vulgare*) in feeding young quails. *Animal Science and Food Technology*, 16(2), 9-22. doi: 10.31548/animal.2.2025.09.

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qualities of meat-type quails. According to the results of the experiment, among the investigated doses of fennel seed cake, specifically 0.5%, 1.0%, and 1.5%, the highest productivity was achieved by birds consuming full-feed compound feed containing 1.5% of the mentioned feed additive. The quails in this group exceeded the control group by 9.75 g or 3.44% in weight. With 1.0% fennel seed cake in the compound feed, the body weight of the birds was 7.07 g or 2.50% higher than the control group. When consuming compound feed containing 0.5% fennel seed cake, the quails surpassed the control group by only 4.55 g or 1.61%. It should be noted that the difference between the groups in terms of body weight was not statistically significant. The yield of carcasses slightly differed from the control, with quails consuming 1.5% fennel seed cake in the feed having a 0.1% higher yield. Regarding the yield of edible parts of the carcass, the trend towards an increased yield of breast muscles in the birds of the experimental groups was noteworthy, as well as the increased yield of the stomach, which was confirmed by the statistical significance of the difference between the control group and the birds consuming 1.5% fennel seed cake. Thus, it can be stated that feeding up to 1.5% fennel seed cake in full-feed compound feed has a positive effect on the productivity of meat-type quails

Keywords: phytobiotics; productivity; poultry meat production; slaughter qualities; oil production waste

Introduction

Before the introduction of the ban on the use of antibiotics in poultry farms, these substances were commonly used in the feeding of young poultry for several important reasons. First and foremost, they helped maintain the health of the birds by preventing bacterial infections and reducing the risk of diseases that could negatively affect the growth and development of young individuals. Furthermore, the use of antibiotics contributed to improved livestock survival rates, as they reduced mortality and ensured stable conditions for raising the birds. Another important aspect was their ability to enhance productivity, as antibiotics stimulated growth, improved feed conversion, and facilitated more efficient weight gain. Thus, prior to the ban, antibiotics played a significant role in ensuring high productivity in poultry farming, contributing to the effective raising of poultry and the production of high-quality products (Alabi *et al*., 2023).

Since poultry farming was the largest consumer of feed antibiotics, it is not surprising that interest in researching alternatives to these substances has grown most significantly in this area. Among the various approaches that can replace feed antibiotics, the use of plant-based products shows promise, as they possess a wide range of beneficial properties. Plant extracts, essential oils, phytobiotics, and other natural components can exhibit antimicrobial effects, stimulate the immune system of poultry, and improve feed utilisation. Many plant compounds, such as flavonoids, alkaloids, tannins, and phenols, have anti-inflammatory and antioxidant properties, which help reduce stress levels in birds and improve their overall health. Additionally, plant-based products can positively impact gut microbiota, stimulating the growth of beneficial bacteria and inhibiting the development of pathogenic microorganisms. This approach not only enhances poultry productivity and survival but also ensures environmentally safe production that meets modern consumer demands for healthy food and the elimination of antibiotics in animal husbandry (Aktaran Bala, 2023; Arif *et al*., 2024).

According to M. Rafeeq *et al*. (2022), phytobiotics are a wide range of plant-derived compounds with varying chemical compositions that exhibit antimicrobial, anticoccidial, antifungal, antioxidant, immunostimulatory, anti-stress properties and influence the gut microbiota. The scientific works of R. Islam & I. Sheikh (2021) and J. Urban *et al*. (2024) reveal the mechanism of action of active plant substances on physiological processes in animals. In the study by R. Islam & I. Sheikh (2021), a series of experiments were conducted on different types of agricultural animals, examining the impact of various phytobiotic additives on the digestive system. The results showed that the inclusion of extracts from plants such as garlic (*Allium sativum*), ginger (*Zingiber officinale*), and cinnamon (*Cinnamomum verum*) in the diet led to a significant increase in saliva production. This, in turn, facilitated better feed wetting and the initial breakdown of carbohydrates by amylase present in the saliva. Additionally, there was an observed increase in gastric juice secretion, pancreatic enzymes, and bile, which ensured more efficient breakdown of proteins, fats, and carbohydrates in the gastrointestinal tract. These changes resulted in improved dry matter digestibility and an increased absorption rate of key nutrients such as amino acids, fatty acids, and glucose. As a result, the animals showed higher body weight gain and improved feed conversion, which are key performance indicators in animal husbandry.

In turn, J. Urban *et al*. (2024) focused on studying the impact of phytobiotics on the gut microbiota and its role in the digestion process. The study showed that the inclusion of plant extracts rich in essential oils, such as oregano (*Origanum vulgare*) and thyme (*Thymus vulgaris*), in the animals' diet contributed to the modulation of the gut microbiota composition. Specifically, there was an increase in the number of beneficial bacteria from the genera *Lactobacillus* and *Bifidobacterium*, which play an important role in the fermentation of undigested feed residues and the synthesis of short-chain fatty acids. These acids serve as an additional energy source for the intestinal epithelium and help maintain its barrier function. Moreover, under the influence of phytobiotics, the number of pathogenic microorganisms, such as *Escherichia coli* and *Salmonella* spp., decreased, reducing the risk of infectious diseases and inflammatory processes in the gut. The improvement of the microbial balance and reduction of inflammation contributed to the optimisation of digestion and nutrient absorption processes, which in turn positively affected the overall productivity of the animals. Both studies highlight the importance of a comprehensive approach to using phytobiotics in the feeding of agricultural animals. Stimulating endogenous digestive processes through increased saliva, enzyme, and bile secretion, as well as modulating the gut microbiota, are key mechanisms by which plant additives improve digestibility and nutrient absorption. This, in turn, leads to increased animal productivity, reduced feed costs, and improved economic indicators for farms.

After analysing a significant number of scientific works, M. Alghirani *et al*. (2021) state that it has been experimentally confirmed that phytobiotics such as cinnamon, caraway, oregano, clove, thyme, rosemary, sage, green tea, garlic, fenugreek, pepper, ginger, and others, due to their properties, contribute to improving feed consumption and nutrient absorption, which results in increased poultry productivity, improved carcass characteristics, and meat quality. The research by Yu. Balji *et al*. (2024) confirms the positive impact of compound feed with extruded components and phytobiotics on the quail organism, while I. Ibatullin *et al*. (2022) demonstrate their effectiveness in increasing the productivity of meat-type quail.

One of the numerous groups of phytobiotics is fennel. According to A. Ullah *et al*. (2024),

the seeds of this plant and its processed products have shown effectiveness in the prevention and treatment of respiratory and gastrointestinal disorders due to their antibacterial, antioxidant, and immunomodulatory properties, which contribute to improved poultry productivity and strengthened health. Including fennel in the poultry diet can reduce oxidative stress, enhance immune response, and improve the overall health of the birds. Most of the studies described in the current scientific literature use fennel seeds or fennel oil as a feed additive in animal feeding. Previous research has demonstrated the positive effects of fennel oil and seeds on the productivity of meat-type quail. However, fennel cake – the by-product of oil production – remains less studied. The aim of this study was to evaluate how the inclusion of fennel seed cake in the diet of meat-type quail affects their growth and meat quality.

Materials and Methods

The scientific and production experiment was conducted in the spring of 2024 at the "Schambachtal Alpakas" farm (Germany). For the scientific and production experiment to determine the optimal share of fennel cake, 400 one-day-old Pharaoh quail chicks were selected and divided into four analogous groups, with 100 birds in each group. The first group was the control group, while the second, third, and fourth groups were experimental. The animals were kept in cages located in a facility with regulated microclimate parameters. The birds had 24/7 access to water and feed. The control group quails were fed complete compound feeds formulated based on standard recipes, while the feed for the third and fourth groups included fennel meal in the amounts indicated in Table 1.

The recipes of compound feeds consumed by meat-type quail during the scientific and economic experiment are presented in Table 2.

Table 1. *Scheme of scientific and economic experiment*

№ of group	Purpose of group	Feeding conditions
1	Control	Complete feed (CF)
2	Experimental	CF with fennel seed meal content of 5 g/kg (0.5%)
3	Experimental	CF with fennel seed meal content of 10 g/kg (1.0%)
4	Experimental	CF with fennel seed meal content of 15 g/kg (1.5%)

Source: developed by the authors

Table 2. *Composition of complete feeds for feeding quail, %*

Indicator	Age of quail 1-21 days				Age of quail 22-42 days			
	Group							
	Control	Experimental			Control	Experimental		
	1	2	3	4	1	2	3	4
Corn	47.41	47.80	48.20	48.40	59.20	59.31	59.61	60.00
Soybean meal	26.10	26.70	27.30	28.10	20.80	21.55	22.10	22.60
Sunflower meal	5.50	4.00	2.50	1.00	5.50	4.00	2.70	1.30
Fennel seed meal	-	0.50	1.00	1.50	-	0.50	1.00	1.50
Soybean oil	1.55				2.40	2.50		
Fish meal	5.00					4.00		
Gluten meal	2.00					3.50		
Blood meal	8.00					-		
Table salt	0.30					0.50		
Monocalcium phosphate	1.00					1.00		

Table 2. Continued

Indicator	Age of quail 1-21 days				Age of quail 22-42 days			
	Group							
	Control	Experimental			Control	Experimental		
	1	2	3	4	1	2	3	4
Crushed shell	1.00				1.00			
L-Lysine	0.04	0.03		0.02	0.11	0.08	0.07	
L-Threonine	-	0.01			-			
DL-Methionine	0.10	0.11		0.12	0.02			0.03
Premix	2.00				2.00			

Source: developed by the authors

To incorporate fennel seed meal into the composition of compound feeds for poultry, the proportion of sunflower meal and oil was reduced, while the amount of soybean meal was increased. The concentration of corn in the compound feeds also underwent minor changes. To adjust amino acid nutrition at the same level, the inclusion of necessary amino acids was modified. At the same time, the content of nutrients and energy was carefully considered, keeping them at a consistent level. Thus, at the age of 1-21 days, the quail feed contained 28.0% crude protein, 6.5% crude fat, 3.5% crude fibre, 1.79% lysine, 1.01% methionine with cystine, 1.15% threonine, 0.35% tryptophan, 1.0% calcium, 0.8% phosphorus, and 0.4% sodium, with an energy value of 12.5 MJ per kg. Birds aged 22 days and older consumed compound feed with an energy value of 12.9 MJ and a crude protein content of 20.5%, crude fat – 7.3%, crude fibre – 3.4%, lysine – 1.03%, methionine with cystine – 0.74%, threonine – 0.77%, tryptophan – 0.21%, calcium – 1.0%, phosphorus – 0.8%, and sodium – 0.5%. Thus, the nutritional value of the compound feeds for the main nutrients and energy was kept at the same level.

Every week, the quails were weighed, and the survival rate of the chicks and feed consumption were monitored. At the age of 42 days, a control slaughter of the birds was conducted, for which 4 birds were selected from each group, with their weights being as close as possible to the average for the group. The maintenance and slaughter of the birds were carried out in accordance with the requirements of current legislation (European Convention, 1986; Council Directive 1998/58/EU, 1998; Council Directive 1999/74/EC, 1999; Council Directive 2010/63/EU, 2010; Law of Ukraine No. 3447-IV, 2006).

Results and Discussion

Body weight is the primary method for assessing poultry productivity during meat production. During the scientific and economic experiment, these indicators were monitored weekly by weighing the quails (Table 3).

Table 3. *Dynamics of body weight of the experimental quails, g*

Group	Age, days						
	1	7	14	21	28	35	42
1 Control	10.01± 0.053	39.98± 0.317	93.73± 0.482	148.73± 2.278	202.03± 2.546	241.07± 3.142	283.25± 4.454
2 Experimental	10.05± 0.057	40.34± 0.304	94.55± 0.601	151.69± 1.923	205.08± 2.680	245.10± 3.498	287.80± 4.487
3 Experimental	10.02± 0.058	40.58± 0.321	95.51± 0.594*	151.99± 2.076	206.43± 2.618	247.42± 3.528	290.32± 4.110

Table 3. Continued

Group	Age, days						
	1	7	14	21	28	35	42
4 Experimental	9.98± 0.050	40.77± 0.318	96.96± 0.574**	152.73± 2.112	207.98± 2.622	249.33± 3.313	293.00± 4.462

Note: *P < 0.05, **P < 0.01 compared to the 1st control group
Source: developed by the authors

At the beginning of the scientific and economic experiment, the birds of the control and experimental groups were balanced by body weight, so the difference between the groups did not exceed 0.07 g or 0.7%. At the age of 7 days, the quails of the 4th experimental group showed the greatest advantage over the control in live weight – by 0.79 g or 1.98%. The advantage of the birds in the 3rd experimental group was somewhat smaller – 0.60 g or 1.50%. The quails of the 2nd experimental group differed least from the control, surpassing the control birds by 0.36 g or 0.90%. This difference was not statistically significant. Two weeks after the start of the scientific and economic experiment, the difference between the birds in the 3rd and 4th experimental groups and the control was 1.78 g or 1.90% and 2.23 g or 2.38%, respectively, and was statistically significant. The advantage of the birds in the 2nd experimental group at this age was 0.82 g or 0.87%.

Weighing of the quails at the age of 21 days showed the previously established trend. The leading body weight indicators were observed in the birds of the 4th experimental group, exceeding the control counterparts by 4.00 g or 2.69%. The birds in the 3rd and 2nd experimental groups exceeded the control by 3.26 g and 2.96 g, or 2.19% and 1.99%, respectively. The difference in body weight between the groups at this age was not statistically significant. At the end of the fourth week of rearing, the body weight of the birds in the 4th experimental group showed an advantage over the control by 5.95 g or 2.95%. The difference between the control and the birds in the 3rd experimental group was somewhat smaller – 4.40 g or 2.18% in favour of the experimental group. The birds in the 2nd experimental group surpassed the control counterparts in body weight by the least amount – by 3.05 g or 1.51%. As in the previous weighing, at the age of 28 days, the difference in body weight between the groups was not statistically significant.

The penultimate control weighing showed no changes in the distribution of leading positions between the groups. The animals in the 4th experimental group continued to demonstrate the highest body weight, exceeding the control counterparts by 8.26 g or 3.43%. The birds in the 3rd experimental group surpassed the control by 6.35 g or 2.63%. The birds in the 2nd experimental group differed least from the control during this period, surpassing the control by 4.03 g or 1.67%. No statistically significant difference between the groups was found during this weighing. The final weighing of the birds, conducted at the age of 42 days, once again confirmed that the greatest advantage in body weight over the control animals was recorded in the birds of the 4th experimental group – by 9.75 g or 3.44%. The quails in the 3rd experimental group also surpassed the control counterparts in this indicator by 7.07 g or 2.50%. The quails in the 2nd experimental group had the smallest difference in body weight from the control animals – by 4.55 g or 1.61%. It is worth noting that there was no statistically significant difference between the animals of the different groups.

Analysing the survival rate of the quails, it can be stated that there was no dependence between the proportion of fennel seed meal in the compound feeds and the mortality of the birds.

During the entire scientific and economic experiment, the losses of quails in the 1st control, 3rd, and 4th experimental groups amounted to 7 birds in each group, which is 7% in percentage terms. The mortality rate in the 2nd experimental group was 8 birds, or 8%, which was 1% higher than the control value. Analysing the feed consumption per unit of body weight gain in quails throughout the entire scientific and economic experiment, it can be noted that this indicator was the highest in the birds of the 1st control group and the lowest in the animals of the 4th experimental group. Therefore, the birds in the 4th experimental group had a disadvantage compared to the control group by 125 mg/g or 3.30%. At the same time, the birds in the 3rd and 2nd experimental groups also had a disadvantage compared to the control animals by 69 mg or 1.82% and 47 mg or 1.24%, respectively.

Most often, quail are marketed to the final consumer in the form of dressed carcasses. According to the research results, the weight of the dressed carcass of the birds in the 2nd experimental group was 2.8 g or 1.33% higher than the control indicator. The advantage of the birds in the 3rd experimental group over the control was 5.4 g or 2.57%. The quails in the 4th experimental group surpassed the control by 7.4 g or 3.52% in the weight of the dressed carcass. The difference between the birds in the 4th experimental group and the control group for the weight of the dressed carcass was statistically significant. For an objective assessment of the slaughter qualities of the quails, a comparison of the yield of semi-dressed and dressed carcasses was conducted (Table 4).

The yield of semi-dressed carcass in the 2nd and 3rd experimental groups was identical to the control indicator. In the birds of the 4th experimental group, the yield of the semi-dressed carcass was 0.1% higher than in the control counterparts. A similar difference was observed between the animals of the different groups for the weight of the dressed carcass. Specifically, the quails of the 2nd and 3rd experimental groups were equal to the control animals, while the 4th experimental group surpassed the control by 0.1%. Changes in the feeding of quails had an impact on their growth, but it is important to know which tissues and organs contributed to the increase in body weight (Table 5).

Table 4. *Slaughter qualities of quails, % of pre-slaughter weight*

Indicator	Group			
	Control	Experimental		
	1	2	3	4
Yield of semi-dressed carcass	81.0±0.20	81.0±0.20	81.0±0.17	81.1±0.20
Yield of dressed carcass	73.8±0.25	73.8±0.23	73.8±0.25	73.9±0.25

Source: developed by the authors

Table 5. *Weight of edible parts, g*

Indicator	Group			
	Control	Experimental		
	1	2	3	4
Breast muscles	47.9±0.68	48.9±0.59	49.4±0.65	49.8±0.24
Leg muscles	29.4±0.27	30.1±0.32	30.3±0.34	30.4±0.37
Skin	17.9±0.28	18.1±0.17	18.2±0.38	18.3±0.24
Internal fat	2.2±0.11	2.3±0.09	2.3±0.08	2.3±0.09
Liver	6.8±0.09	6.8±0.08	6.9±0.10	6.9±0.04
Lungs	2.5±0.06	2.5±0.07	2.5±0.08	2.6±0.09
Kidneys	1.5±0.05	1.5±0.05	1.5±0.13	1.5±0.05

Table 5. Continued

Indicator	Group			
	Control	Experimental		
	1	2	3	4
Gizzard muscles	5.2±0.09	5.4±0.19	5.5±0.18	5.6±0.06*
Heart	2.2±0.05	2.3±0.11	2.4±0.13	2.4±0.12

Source: developed by the authors

The difference in the mass of breast muscles between the control and experimental groups of quails was quite significant, though statistically not meaningful. The birds in the second experimental group had 1.0 g or 2.09% more breast muscle mass compared to the control group, the third experimental group had 1.5 g or 3.13% more, and the fourth experimental group had 1.9 g or 3.97% more. The mass of the lower limb muscles in the birds of the second experimental group was 0.7 g or 2.38% higher than that of the control animals. The third experimental group had 0.9 g or 3.06% more, and the fourth experimental group had 1.0 g or 3.40% more. The animals in the second experimental group had 0.2 g or 1.26% more skin mass than the control group. The third experimental group had a slightly greater advantage, 0.3 g or 1.68%, over the control group. The largest difference was observed in the fourth experimental group, with a 0.4 g or 2.23% higher skin mass than the control animals.

Due to the mass of internal fat, quails in all experimental groups exceeded the control animals by 0.1 g or 4.55%. The liver mass of the quails in the second experimental group was identical to the control value. The animals in the third and fourth experimental groups exceeded the control animals by 0.1 g or 1.47%. The quails in the second and third experimental groups had equal lung mass to the control counterparts. However, the animals in the fourth experimental group exceeded the control animals in this indicator by 0.1 g or 4.00%. In terms of kidney mass, the quails in the experimental groups were equal to the control counterparts. The muscle stomach mass in the birds of the second experimental group was greater than that of the control group by 0.2 g or 3.85%. The quails in the third experimental group exceeded the control counterparts by 0.3 g or 5.77%. The greatest and statistically significant advantage over the control was observed in the animals of the fourth experimental group, which was 0.4 g or 7.69%. In the birds of the second experimental group, the heart mass was higher than the control value by 0.1 g or 4.55%. The quails in the third and fourth experimental groups exceeded the control animals in heart mass by 0.2 g or 9.09%. To simplify the evaluation of the changes that occurred upon the introduction of fennel meal into the compound feed, a calculation was made of the yield of edible body parts of the quails – the ratio of their mass to the mass of the dressed carcass (Table 6).

Table 6. *Yield of edible parts, % of the pre-slaughter body weight*

Indicator	Group			
	Control	Experimental		
	1	2	3	4
Breast muscles	16.82±0.170	16.95±0.130	16.94±0.180	16.91±0.090
Leg muscles	10.35±0.060	10.44±0.050	10.37±0.120	10.33±0.150
Skin	6.30±0.110	6.27±0.090	6.24±0.110	6.23±0.090
Internal fat	0.78±0.040	0.78±0.030	0.78±0.030	0.79±0.030

Table 6. Continued

Indicator	Group			
	Control	Experimental		
	1	2	3	4
Liver	2.39±0.020	2.37±0.020	2.36±0.020	2.35±0.010
Lungs	0.87±0.020	0.87±0.020	0.87±0.020	0.88±0.030
Kidneys	0.52±0.020	0.51±0.020	0.51±0.040	0.51±0.020
Gizzard muscles	1.83±0.020	1.88±0.050	1.89±0.050	1.91±0.020
Heart	0.79±0.010	0.79±0.040	0.81±0.040	0.81±0.040

Source: developed by the authors

The leader among the experimental groups in terms of the yield of breast muscles was the quails of the second experimental group, exceeding the control animals by 0.13%. The advantage of the birds in the third experimental group over the control counterparts was slightly lower, specifically 0.12%. The smallest difference from the control was observed in the animals of the fourth experimental group, which exceeded the control value by 0.09%. In terms of the yield of lower limb muscles, quails in the second and third experimental groups surpassed the control animals by 0.09% and 0.02%, respectively, while the birds in the fourth experimental group were inferior to the controls by 0.02%. The skin yield in quails of the second, third, and fourth experimental groups was lower than the control by 0.03%, 0.06%.

In the quails of the second and third experimental groups, as well as the first control group, the yield of internal fat was the same. The animals in the fourth experimental group exceeded the control animals by 0.01% in this indicator. The liver yield in the quails of the second experimental group was 0.02% lower than the control. The animals in the third experimental group were inferior to the control counterparts by 0.03%, and the birds in the fourth experimental group by 0.04%. The birds in the second and third experimental groups, as well as the quails in the first control group, had the same lung yield. The animals in the fourth experimental group exceeded the control animals by 0.01% in this indicator. The kidney yield in the birds of the experimental groups was the same and 0.01% lower than the control value. The advantage of the birds in the second experimental group over the control in terms of muscle stomach yield was 0.05%. The animals in the third experimental group exceeded the control counterparts by 0.06%, and the representatives of the fourth experimental group by 0.08%. The animals in the third and fourth experimental groups exceeded the control in terms of heart yield by 0.02%, while the birds in the second experimental group were equal to the control in this indicator.

In the last two decades, phytogenic substances found in plants have become increasingly popular as feed additives in poultry farming. In their review, M. Kumar *et al*. (2014) propose over 20 different feed additives with antimicrobial, anti-inflammatory, antioxidant, and immunostimulatory properties for use in animal feeding. N. Abdelli *et al*. (2021) add that the positive impact of phytobiotic feed additives on animal productivity can be explained by their ability to enhance feed efficiency by stimulating the production of digestive secretions, improving nutrient absorption, as well as reducing pathogenic load in the intestine and decreasing the strain on the animals' immune system.

There is limited data in the available scientific literature on the use of fennel meal in animal and poultry feeding. In studies by M. Henda (2014) conducted on young Japanese quails, the effectiveness of including fennel meal at 0.25 g, 0.50 g, or 0.75 g per 1 kg of compound feed was examined. The best feed conversion

and body weight gains were observed at a fennel meal dose of 0.5 g/kg, but other tested levels of the feed additive also contributed to improved poultry productivity and feed efficiency. Additionally, the study noted a slight increase in the yield of the heart, liver, and stomach. These results align with current research findings, which recorded increased productivity, feed consumption, and yields of the stomach and heart. However, the liver yield, according to the experiment described in this article, was reduced.

It is also worth considering the results of feeding Japanese quails aged 15-42 days with complete compound feeds containing 5-15% papaya leaf meal, published by K. Ampode (2019). Positive changes in quail productivity and feed conversion were noted only at the 5% papaya leaf meal dose. At 10% of this feed additive, the productivity of the birds was equal to the control, but feed conversion was better than the control values. The inclusion of 15% papaya leaf meal in the compound feed was worse than the control data in both productivity and feed conversion.

Conflicting data were obtained from the use of ginger meal in broiler chick feeding. S. Ndams *et al*. (2024), when feeding chicks with 0.1%, 0.2%, and 0.3% ginger meal in the compound feed, noted a positive effect only at the 0.2% dose. At this level of ginger meal in the feed, an increase in body weight gain, feed consumption, and feed conversion was recorded. It is important to note that similar indicators in the birds consuming diets with 0.1% and 0.3% ginger meal were lower than the control.

Feeding broiler chicks with various doses of cashew nut meal in compound feeds showed that the addition of 2% positively affected chick growth, feed consumption, and feed conversion. H. Yusuf & M. Aliyu-Paiko (2020) claim that increasing the proportion of cashew nut meal to 4% negatively affected these indicators, as their levels worsened relative to the control.

Regarding the use of fennel, most of the conducted studies focus on the use of oil or ground seeds in poultry feeding. In particular, K. Premavalli & A. Omprakash (2020) concluded that the highest productivity in terms of body weight, feed conversion, and survival of young quails was achieved at a 1.5% fennel seed dose in the compound feed. At the same time, the inclusion of this feed additive at 0.5% and 1.0% was also effective, but with lower results.

Slaughter quality of adult quails fed 2.0% fennel seed in the complete compound feed in the studies by N. Coşkun Çetin *et al*. (2022) was significantly higher than the control values. Positive effects on the slaughter qualities of quails were also observed at 1.0% and 4.0% fennel seed concentrations in the feed mixture.

In previous studies by the authors of this paper, the inclusion of 0.1-0.3% fennel oil in the compound feed resulted in an increase in average daily weight gain by 0.34-0.46 g, or 5.22-7.07% compared to the control, an increase in feed consumption by 2.41-4.49%, a decrease in feed conversion by 5.04-6.97%, and an improvement in the slaughter qualities of the birds. The best results were observed in quails whose compound feed contained 0.3% fennel oil. Thus, the inclusion of fennel meal has a slight positive effect on the productivity of quails with a meat production focus. However, the addition of fennel oil or seeds has a greater impact on the productivity of these animals, as evidenced by the results of various studies.

Conclusions

The main biologically active compounds of fennel that have antimicrobial properties are found in its oil, the content of which in the meal is minimal. This is why the effect on productivity was minimal with the addition of a small amount of this phytobiotic. Based on the results of the experiment, it can be stated that the use of fennel seed meal in the feeding of meat-type quails aged up to 42 days, at a dose of 0.5-1.5% in complete compound feeds, positively affects the growth of these animals, their survival, and slaughter indicators.

Among the tested doses of the specified feed additive, the highest growth rates were observed in the birds whose compound feed contained 1.5%. The weighing results showed that the quails in this experimental group demonstrated the greatest growth dynamics. At 7 days of age, their weight exceeded the control by 1.98%, and by 42 days, this difference increased to 3.44%. At the same time, the quails in the second and third experimental groups also had higher body weight, but with a less pronounced trend. The animals in this group also demonstrated the best feed conversion rate. Lower concentrations of fennel meal also had a positive effect on the animals' productivity, but the difference compared to the control group was minimal.

The analysis of slaughter qualities of the quails indicates a positive effect of feeding with fennel meal on the final productivity of the birds. The highest carcass weight was recorded in the quails of the experimental group, whose compound feed contained 1.5% fennel meal. It is worth noting that in the birds of the experimental groups, an increase in the weight of the breast muscles, lower limb muscles, and the gizzard was observed. The highest indicators for these criteria were also observed in the quails that consumed compound feed with 1.5% fennel meal. In the future, it will be relevant to study the optimal combination of different forms of fennel (oil, seeds, and meal) in the compound feeds of meat-type quails to achieve the best zootechnical indicators, product quality, and economic efficiency.

Acknowledgements

None.

Funding

None.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Ефективність використання шроту фенхелю (*Foeniculum vulgare*) у годівлі молодняку перепелів

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Анотація. Насіння фенхелю вважається потужним фітобіотиком і може бути використане у годівлі молодняку птиці як альтернатива антибіотикам, які застосовують з метою покращення продуктивності птиці та профілактики низки захворювань шлунково-кишкового тракту. Проведений науково-господарський дослід був присвячений дослідженню впливу згодовування шроту з насіння фенхелю на продуктивність та забійні якості перепелів м'ясного напряму продуктивності. За результатами експерименту серед досліджуваних доз шроту фенхелю, а саме 0,5 %, 1,0 % та 1,5 %, найвищої продуктивності досягла птиця, яка споживала повнораціонні комбікорми з вмістом 1,5 % вказаної кормової добавки. Перепели цієї групи перевищили контрольні показники за масою на 9,75 г або 3,44 %. За вмісту 1,0 % шроту фенхелю у складі комбікорму маса тіла птиці була на 7,07 г або 2,50 % вищою за контроль. Споживаючи комбікорми з вмістом 0,5 % шроту фенхелю, перепели переважали контрольний показник за масою тіла лише на 4,55 г або 1,61 %. Різниця між групами за масою тіла не була статистично значущою. За виходом тушки від контролю незначно відрізнялися, а саме переважали на 0,1 % лише перепели, що споживали з кормом 1,5 % шроту фенхелю. За виходом їстівних частин тушки привернула увагу тенденція до збільшення виходу м'язів

грудей у птиці дослідних груп, а також підвищення виходу шлунку, яке було підтверджене статистичною значущістю різниці між контрольною групою перепелів та птицею, яка споживала 1,5 % шроту фенхелю. Таким чином, можна стверджувати, що згодовування до 1,5 % шроту фенхелю у складі повнораціонних комбікормів позитивно впливає на продуктивність перепелів м'ясного напряму продуктивності

Ключові слова: фітобіотики; продуктивність; м'ясне птахівництво; забійні якості; відходи олійноекстракційного виробництва

ANIMAL SCIENCE AND FOOD TECHNOLOGY

Journal homepage: https://animalscience.com.ua/en
Animal Science and Food Technology, 16(2), 23-38
Received 16.01.2025 Revised 01.05.2025 Accepted 22.05.2025

UDC 636.32/.38
DOI: 10.31548/animal.2.2025.23

Growth and meat productivity of lambs depending on the genotype according to the A blood group system of their mothers

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Abstract. The Askaniy fine-wool breed of sheep is known for its high meat and wool productivity, as well as its adaptability to steppe conditions, making it a valuable subject for breeding research. This study aimed to investigate the relationship between maternal genotypic characteristics and key lamb productivity indicators to improve the efficiency of breeding programmes. The research

Suggested Citation:
Luhovyi, S., Bondar, A., Danylchuk, H., & Onyshchenko, L. (2025). Growth and meat productivity of lambs depending on the genotype according to the A blood group system of their mothers. *Animal Science and Food Technology*, 16(2), 23-38. doi: 10.31548/animal.2.2025.23.

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was conducted from 2022 to 2024 at the Educational, Scientific and Practical Centre of Mykolaiv National Agrarian University (Ukraine). The sample comprised 60 clinically healthy Askaniy fine-wool ewes aged 2 to 5 years, all kept under uniform conditions, with minimal fertility variation and no hereditary pathologies. The most prevalent maternal genotype was A(-), associated with stable reproductive performance. The Ab genotype exhibited the highest milk yield and fertility, while Aa showed balanced characteristics. The Aab genotype was notable for high fertility and frequent multiple births. Lambs born to dams with the Ab genotype had the highest average birth weight (4.2 kg), daily weight gain (180 g), and weaning weight (18.2 kg). The lowest productivity indicators were observed in the A(-) group, although this group displayed strong adaptive traits. At seven months, lambs from Ab dams showed the highest slaughter weight (21.4 kg) and meat yield (53%), outperforming the Aa, A(-), and Aab groups. The maternal genotype also influenced fat content, bone ratio, and meat quality. These results confirmed that maternal genotype significantly affected lamb productivity, with the Ab genotype showing the greatest potential in terms of growth, milk production, and meat yield, highlighting its value for selective breeding programmes

Keywords: breeding; slaughter weight; fertility; milk production of sheep; Askaniy fine-wool breed

Introduction

The relevance of this study stems from the growing importance of livestock productivity in agriculture – particularly in sheep breeding, where traits such as growth rate, meat yield, and adaptive capacity are of key economic and practical significance. Breeding highly productive sheep breeds with enhanced growth and meat qualities is a strategic priority for meeting the demand for quality animal products, especially in steppe regions characterised by challenging climatic conditions. In this context, particular attention must be paid to the genetic factors influencing productivity, with blood groups playing a prominent role as potential productivity markers.

Research into the relationship between genetic characteristics – particularly phenogroups defined by blood group systems – and animal productivity represents a promising area of investigation. Blood groups can serve not only as markers of performance traits but also as influencing factors in growth, development, and both meat and wool productivity (Dossybayev *et al.*, 2024). Previous studies have demonstrated that phenotypic and genotypic traits are instrumental in determining both productivity and adaptability in sheep. For instance, I. Hladii (2022) focused on the biochemical blood parameters of young sheep from different genotypes, revealing significant differences influenced by genetic factors such as metabolism, resistance to environmental stressors, and physiological development. These findings underscore the critical role of genetic variability in assessing productivity and its potential for enhancing sheep breeding practices.

The applied value of such research is evident: the results can be directly implemented to improve breeding programmes and increase the economic efficiency of sheep production. This approach is further supported by S. Luhovyi *et al.* (2020), who emphasised the prospects of genomic selection methods in improving sheep production quality. Their work proposed molecular-genetic approaches, including the identification of productivity-associated markers for traits such as adaptability and disease resistance. These methods represent innovative solutions within the industry, promoting more effective use of genetic resources in breeding efforts (Ruban & Danshin, 2023). The relevance of this research is further

confirmed by international studies. For example, D. Karthik *et al.* (2021) examined the effects of different housing systems on the growth, productivity, and stress resistance of sheep. The study focused on physiological adaptation to environmental conditions, including temperature stress and feed variability, demonstrating the necessity of a comprehensive approach that integrates both genetic and environmental factors. Their findings reinforced the role of optimised management practices in enhancing the overall efficiency of sheep farming systems. Despite growing interest in this field, a key challenge remains the lack of sufficient data on the relationship between blood groups and sheep productivity, which limits the practical application of blood group systems in breeding. In addressing this gap, the study by E. Mukhtarov *et al.* (2022) analysed the dynamics of several blood parameters in sheep – specifically haemoglobin, erythrocyte, and leukocyte levels – which serve as important biomarkers for assessing health and productivity potential. These findings emphasise the role of physiological and biochemical monitoring in understanding metabolic processes and optimising husbandry conditions.

The study by F. Alshamiry *et al.* (2023) investigated the influence of various feeding regimes on the growth and meat productivity of lambs. The authors focused on analysing the fatty acid composition of meat, which serves as a key indicator of nutritional value. Their findings demonstrated that modifications in diet significantly affect not only growth performance but also the ratio of saturated to unsaturated fatty acids, offering practical insights into improving meat quality in line with modern consumer demands. In the work of V. Iovenko *et al.* (2021), a novel method was proposed for assessing and predicting meat productivity in sheep. This method integrates biological, genetic, and performance indicators, allowing the identification of potentially productive animals at early stages of development. Such a tool presents substantial value for enhancing selection processes within breeding programmes.

M. Gill *et al.* (2021) explored polymorphisms in genes related to protein and lipid metabolism in modern Ukrainian cattle breeds. Their research demonstrated that certain genetic markers may act as indicators of high productivity and environmental adaptability. This study contributed to the scientific discourse by highlighting the role of molecular genetic research in elucidating key mechanisms of metabolic regulation in livestock. Further, Y. Gritsienko *et al.* (2022) established a correlation between genetic markers and performance traits in dairy cattle breeds, underscoring the applicability of genetic indicators across various branches of animal husbandry. These findings can be adapted for use in meat-producing sheep breeds, reinforcing the potential of molecular genetic approaches in breeding strategies.

The purpose of the study was to determine the influence of maternal genetic characteristics, specifically within the A blood group system, on the productivity of lambs – focusing on their growth, development, and meat performance – in order to optimise breeding programmes and enhance the efficiency of selecting high-yielding sheep. Objectives of the study:

- to assess the influence of different maternal genotypes within the A blood group system on early lamb growth, particularly live weight gain and weaning weight;
- to investigate the relationship between maternal genetic characteristics and the meat productivity of lambs, specifically slaughter weight and meat yield;
- to determine statistical patterns in the influence of maternal phenogroups on the performance traits of offspring for their potential use in future breeding strategies.

Materials and Methods

The study was conducted from 2022 to 2024 at the Educational, Scientific and Practical Centre of Mykolaiv National Agrarian University

(Ukraine). The object of the research was sheep of the Askaniy fine-wool breed, known for its high meat and wool productivity as well as its adaptability to the climatic conditions of steppe regions. These characteristics make it a valuable breed for breeding and productivity studies. A sample of 60 clinically healthy ewes aged between 2 and 5 years was selected for the study. All animals were maintained under identical conditions in terms of housing, feeding, and care. The ewes were housed in rooms with a total area of 50 m^2, ensuring a minimum of 2 m^2 per animal. Environmental conditions were controlled, with a stable indoor temperature of 18-20°C and relative humidity maintained between 60-70%. The animals were grouped in flocks of 15, facilitating optimal social interaction. The feeding regime consisted of a balanced diet including 1.5 kg of hay and 0.5 kg of concentrated feed per ewe per day, along with unrestricted access to fresh water. Mineral supplements were added to ensure a full spectrum of essential nutrients. The sample included only ewes with minimal fertility (i.e. those having given birth to a single lamb), free from hereditary pathologies, and confirmed as belonging to the Askaniy fine-wool breed. Representativeness was ensured by selecting animals from different breeding lines and families to minimise the risk of inbreeding. Ewes with genetic abnormalities, chronic diseases, or those that did not meet the requirements of blood group testing were excluded from the sample.

To determine fertility and the frequency of multiple births, zootechnical records from the period 2020-2023 were used. Fertility was calculated as the average number of lambs born per ewe per year. Each litter was recorded, noting the number of viable lambs. The frequency of multiple births was calculated as the percentage of ewes that produced twins or triplets out of the total number of ewes that gave birth within each group. The data were averaged separately for each maternal genotype. Milk yield was assessed using an electronic lactograph (Waikato Milk Meter MK4, accuracy ±0.05 L). Measurements were carried out within the first seven days post-lambing, during which peak lactation occurs. Milk volume was automatically recorded during each milking session (twice daily at 06:00 and 18:00). The average daily milk yield was calculated by averaging the results of all 14 milking sessions for each ewe individually.

The blood group of each ewe was determined via an agglutination reaction using standard isohemagglutinins. The analysis was performed with the "Vet Agglu Test" reagent kit (Germany). Blood samples were collected from the jugular vein using sterile vacuum tubes containing K3 EDTA anticoagulant (USA). Laboratory tests were conducted using an Eppendorf 5702 centrifuge (Germany) and a Leica DM750 microscope (Switzerland). Agglutination reactions were incubated in a Memmert IN55 thermostat (Germany). Results were interpreted in accordance with the Ukrainian State Standard ISO 15189:2015 (2016).

The study included 158 lambs born to the sampled ewes. Lambs were divided into four groups based on the maternal phenogroup within the A blood group system: Group 1 – lambs from Aa phenogroup mothers; Group 2 – lambs from Ab phenogroup mothers; Group 3 – lambs from Aab phenogroup mothers; Group 4 – lambs from A(-) phenogroup mothers. This grouping allowed for the evaluation of the influence of different maternal phenogroups on the growth and development of offspring. Three main indicators were used to assess lamb growth: birth weight – recorded within the first 24 hours after birth; weekly live weight gains – measured from birth to three months of age; weaning weight – recorded at three months of age, a critical stage in lamb development. Weight measurements were performed using electronic scales "Kern PCB 1000-2" (Germany), providing high precision with an accuracy of up to 0.01 kg. The scales were calibrated prior to each measurement to ensure accuracy.

Additionally, calibration was carried out at least once per month, or following equipment transportation, in accordance with the manufacturer's instructions, to minimise potential errors and ensure the reliability of the results. All measurements were conducted in the morning, before feeding the animals, to eliminate the effect of digestive tract fill on body weight. The collected data were recorded in a measurement log, from which the weekly live weight gains for each lamb were subsequently calculated. To evaluate meat productivity at seven months of age, 40 lambs (10 from each maternal genotype group) were selected for slaughter. Prior to slaughter, the lambs were fasted for 24 hours, with free access to water, to ensure digestive tract emptying. After slaughter, slaughter weight was determined by weighing the paired carcass following removal of the internal organs.

For meat yield assessment, the carcasses were dissected to determine the mass of muscle tissue, adipose tissue, and bone. The ratio of these components was used to evaluate carcass quality and breeding efficiency. Meat quality was assessed through parameters including moisture content, colour, and pH value. Moisture content was measured by drying a muscle tissue sample to constant weight using a "Memmert UF55" drying cabinet (Germany). Meat pH – an important indicator of freshness and stress – was measured using a "Testo 205" portable pH meter (Germany), designed for food applications. Measurements were taken directly from the muscle tissue 45 minutes post-slaughter (pH_{45}) and after 24 hours of chilling at +4°C (pH_{24}). Meat colour was evaluated according to the international CIELAB standard (L*, a*, b*), allowing quantitative assessment of lightness, redness, and yellowness. Measurements were conducted with a "Konica Minolta CM-700d" spectrophotometer (Japan), ensuring high accuracy and standardised results. All assessments were conducted in the enterprise's laboratory in accordance with established protocols and standards for evaluating meat productivity, namely: DSTU ISO 2917:2001 (2003), DSTU ISO 1442:2005 (2008), DSTU 4673:2006 (2011). All results were entered into an electronic database for subsequent analysis and intergroup comparison. The study was conducted in accordance with international standards on the humane treatment of animals, including the European Convention for the Protection of Vertebrate Animals Used for Experimental and Other Scientific Purposes (1986), and the Law of Ukraine No. 3447-IV "On the Protection of Animals from Cruelty" (2006). All data were processed using "Statistica 12.0" software (StatSoft, USA). Intergroup comparisons of mean values were performed using Student's t-test (significance level $p \leqslant 0.05$), and correlations were assessed using Pearson's correlation coefficient. Ninety-five percent confidence intervals were calculated for all key indicators. All measurements were repeated three times to minimise experimental error.

Results

As a result of examining the genotypic structure of 60 Ascanian fine-wool ewes based on the A blood group system, four primary phenogroups were identified: Aa, Ab, Aab, and A(-). The distribution of these phenogroups was uneven, indicating a degree of genetic diversity within the studied population. The most prevalent group was A(-), accounting for 54% of the total, while the Ab group was the least represented, comprising only 8% (Fig. 1).

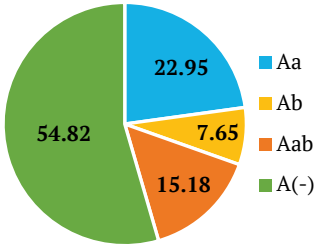

Figure 1. Distribution of ewes by genotype, %
Source: created by the authors

This disparity highlights the genetic diversity within the population and suggests a potential selective advantage of certain genotypes under specific management conditions. Detailed quantitative performance indicators for each group are presented in Table 1.

Table 1. *Performance indicators of the studied groups*

Genotype	Number of ewes (n)	Average fertility (lambs/ewe)	Milk yield (l/day)	Average weight gain of lambs (g/day)	Multiple pregnancy rate (%)
Aa	14	1.1 ± 0.2	1.2 ± 0.3	180 ± 20	5
Ab	5	1.8 ± 0.4	2.5 ± 0.5	250 ± 30	25
Aab	9	2.5 ± 0.6	0.9 ± 0.2	150 ± 25	65
A(-)	32	1 ± 0.3	0.8 ± 0.1	160 ± 15	8

Source: created by the authors

Ewes of the Aa genotype accounted for 23% of the studied sample. The average fertility in this group was 1.1 ± 0.2 lambs per ewe, with 95% of lambs being singletons. A milk yield of 1.2 ± 0.3 litres/day ensured a stable daily weight gain of lambs (180 ± 20 g), corresponding to the average indicators of the breed. Despite its small proportion (8%), the Ab group exhibited extreme performance indicators. The highest milk yield was recorded at 2.5 ± 0.5 litres/day (108% higher than in A(-)), which correlated with the highest weight gain of lambs (250 ± 30 g/day). Fertility (1.8 ± 0.4 lambs per ewe) exceeded the average population level by 64%, and the frequency of multiple births was 25% (mostly twins). These results suggest that the Ab genotype may be key for selection aimed at improving milk production, although its low prevalence warrants further analysis of its genetic potential.

The Aab group demonstrated a combination of characteristics: the highest frequency of multiple births – 65% (mostly twins and triplets), with an average fertility of 2.5 ± 0.6 lambs per ewe. However, milk yield was the lowest (0.9 ± 0.2 litres/day), which limited lamb weight gain (150 ± 25 g/day). This makes Aab valuable for regions with unstable climatic conditions, where offspring survival is a priority. The prevalence of the A(-) genotype (54%) is justified by its versatility. Stable fertility (1.0 ± 0.3 lambs per ewe) and a low frequency of multiple births (8%) ensured predictable litter sizes. Milk yield (0.8 ± 0.1 litres/day) was the lowest among the groups. Lamb weight gain (160 ± 15 g/day) remained stable even under stressful conditions, making this group optimal for farms with limited resources. These data underscore that each genotype possesses unique advantages that can be utilised for targeted breeding, depending on farm priorities (e.g., maximising flock size vs improving product quality). The results show that the most common genotype in the studied population of ewes is A(-), which may reflect its advantages in terms of the productivity of the Ascanian fine-wool breed. At the same time, each group exhibits specific characteristics that define the individual productivity and fertility traits of the animals.

The influence of maternal genotype on lamb growth is a key indicator of productivity and selection efficiency in sheep breeding. The assessment of live weight gain was carried out during the first three months of the lambs' lives – a critical developmental period during which the main parameters of physiological condition and viability are established. The average birth weight of lambs is a crucial determinant of their subsequent development and survival. It largely depends on the maternal genotype, which influences intrauterine development, metabolism, and postnatal lactation performance. The study analysed four genetic groups of dams. Dams in the Ab group gave birth to 48 lambs, with an average birth weight

of 4.2 kg. This was the highest value among all groups, indicating favourable intrauterine conditions and a high level of maternal milk production following lambing. Dams in the Aa group gave birth to 25 lambs with an average weight of 4.0 kg. Although slightly lower, this figure remained high and ensured good neonatal viability. Lambs born to dams of the Aab group had an average weight of 3.8 kg, with a total of 34 lambs in this group. The lower average weight compared to groups Ab and Aa may be attributed to the lower milk yield of the dams and possibly a higher frequency of multiple births (twins or triplets). The lowest average birth weight was observed in lambs from the A(-) group, which included 51 lambs with an average weight of 3.6 kg (Table 2). This may reflect a reduced nutrient supply during gestation and comparatively lower lactation performance of dams in this group.

Table 2. *Influence of maternal genotype on lamb growth*

Indicator	Group Ab (n = 27)	Group Aa (n = 15)	Group Aab (n = 18)	Group A(-) (n = 32)
Number of lambs	48	25	34	51
Average birth weight, kg	4.2	4	3.8	3.6
Average daily gain, g	180	160	155	150
Weight at weaning, kg	18.2	16.8	16	15.6

Note: all indicators were statistically significant ($p < 0.05$)
Source: created by the authors

The results obtained indicate that the genotype of the mothers plays an important role in determining the birth weight of lambs. The highest values observed in the Ab group correlate with elevated lactation levels and overall maternal productivity. Conversely, the lowest figures recorded in lambs from group A(-) mothers may be associated with certain energy limitations during gestation, which likely influenced foetal development. Therefore, selection aimed at increasing birth weight should take into account not only direct genetic factors, but also the physiological status of the mothers, their milk yield, and the level of nutrient provision during pregnancy.

Weekly live weight gains were highest among lambs born to mothers of the Ab group, with an average daily gain of 180 g. This reflects superior lactation performance in the mothers and optimal conditions for lamb development. Lambs from group Aa mothers demonstrated a slightly lower gain of 160 g per day, which may be attributed to moderate maternal milk yield – sufficient for stable, though slightly less intensive, growth. Lambs from Aab group mothers recorded a daily live weight gain of 155 g, lagging behind the Ab group, likely due to reduced lactation levels, especially in cases of twin or triplet births where competition among lambs for resources is higher. The lowest weight gains were observed in lambs from group A(-) mothers, at 150 g per day. All recorded growth rates were statistically significant ($p < 0.05$), indicating a direct effect of maternal genotype on offspring growth. Weaning weight at three months of age also varied depending on maternal genotype. Lambs from Ab group mothers achieved the highest weaning weight at 18.2 kg, reflecting the substantial influence of this genotype on rearing efficiency. Lambs from Aa group mothers had a slightly lower weaning weight of 16.8 kg, which nonetheless remained within the breed's standard range, indicating stable growth. The average weaning weight in the Aab group was 16.0 kg, lower than that of the Ab and Aa groups. The lowest weaning weights were found in lambs from group A(-) mothers, averaging 15.6 kg. Analysis of the data confirms that maternal genotype significantly affects lamb growth and development. Dams with the

Ab genotype provided the most favourable conditions for offspring growth, as reflected in the highest live weight gains and weaning weights. At the age of seven months, 40 lambs (10 from each group) were selected for the assessment of meat productivity. The results demonstrated that the slaughter weight of lambs was influenced by the genotype of their mothers, which strongly correlated with the average birth weight of the lambs and intrauterine development conditions. The highest slaughter weight was recorded in lambs from mothers of the Ab group, with an average of 21.4 kg. This result aligns with the highest average birth weight in this group (4.2 kg) and the superior milk yield of the mothers, which provided optimal conditions for offspring growth and development.

Lambs born to mothers of the Aa group exhibited an average slaughter weight of 20.1 kg. Although slightly lower than the Ab group, this value reflects balanced maternal milk yield and the lambs' capacity to accumulate muscle mass effectively. The relatively high average birth weight of 4.0 kg in this group also provided favourable initial conditions for subsequent development. The lowest average slaughter weight was observed in lambs from mothers of the Aab group, amounting to 19.3 kg. This outcome may be attributed to the group's lower average birth weight (3.8 kg) and a higher incidence of multiple births, which likely resulted in increased competition for milk during the early postnatal period. Reduced maternal milk yield further contributed to the decrease in slaughter weight within this group. Lambs from mothers in the A(-) group had an average slaughter weight of 19.8 kg – lower than that of the Ab and Aa groups but slightly higher than that of the Aab group. These results are consistent with the lowest birth weight observed in the A(-) group (3.6 kg), suggesting limited energy availability during gestation. Nevertheless, the stable fertility and resilience of the ewes in this group helped maintain conditions conducive to lamb development. The results obtained confirm that the genotype of the mothers has a direct influence on the meat productivity of lambs. The Ab genotype is associated with the most favourable slaughter characteristics, including high carcass yield and superior meat quality. Meanwhile, the Aa and A(-) groups demonstrated satisfactory results, making them suitable for use in farms with varying management conditions and production objectives.

Carcass quality, as determined by the ratio of meat, fat, and bone, varied significantly depending on maternal genotype. Lambs born to Ab group mothers exhibited the highest meat yield – 53% of slaughter weight – highlighting the superior muscle development promoted by this genotype, which is a critical factor in meat productivity. Lambs from Aa mothers showed a slightly lower meat yield of 51%, though still at a commendable level. The Aab group lambs had the lowest meat yield at 49%, likely influenced by the genotype's tendency for multiple births and lower milk production, which may affect muscle development. In contrast, lambs from A(-) mothers had a meat yield of 50%, outperforming the Aab group but falling short of Ab and Aa results. In terms of fat yield, the highest value was recorded in lambs from Aa mothers – 26%. This was followed by the Ab group at 24%, the A(-) group at 23%, and the Aab group at 22%, indicating a moderate but consistent variation in adipose tissue accumulation depending on maternal genotype. The bone yield remained relatively consistent across all groups, ranging from 23% to 25% of slaughter weight, suggesting that bone development was less affected by genetic factors in comparison to muscle and fat deposition.

An analysis of the ratios of meat, fat, and bone following carcass dismemberment confirmed that lambs born to Ab group mothers exhibited the highest meat productivity. The ratio of meat to fat and bone in this group was the most favourable among all those studied, indicating superior carcass quality. In Aa group lambs, the ratio was slightly less advantageous

due to a higher fat content, which somewhat reduced the proportion of lean meat. The Aab group showed the lowest meat-to-fat-and-bone ratio, primarily due to a reduced proportion of muscle tissue and a comparatively higher proportion of bone mass. Lambs of the A(-) group demonstrated a meat-to-fat-and-bone ratio exceeding that of Aab, but still lower than in the Ab and Aa groups, suggesting a moderate but noteworthy meat productivity potential. The quality of lamb meat, influenced by the maternal genotype, was assessed through parameters such as moisture content, pH, and colour. Lambs from Ab group mothers had the lowest moisture content (74.3%), which is a desirable trait, indicating better meat quality and reduced water loss during heat treatment. Aa group lambs had a moisture content of 76.1%, while Aab lambs showed the highest value at 77.4%, which may negatively affect texture and shelf-life. Lambs from A(-) group mothers had a moisture content of 75.5%, placing them between the Aa and Ab groups, and lower than Aab (Table 3). The pH values, which serve as indicators of meat freshness and post-mortem biochemical changes, also varied. The Ab group had the lowest pH (5.6), associated with optimal meat quality and good preservation characteristics. The Aa group had a pH of 5.8, the Aab group registered the highest at 6.0, while the A(-) group had a pH of 5.7, comparable to Ab. These findings suggest that lamb meat from A(-) group mothers, despite their lower productivity, possessed better organoleptic qualities than that from Aab group mothers. This highlights the importance of considering both quantitative and qualitative traits in breeding programmes.

Table 3. *Indicators of lamb meat productivity according to maternal genotype*

Indicator	Group Ab	Group Aa	Group Aab	Group A(-)
Average birth weight (kg)	4.2	4	3.8	3.6
Average slaughter weight (kg)	21.4	20.1	19.3	19.8
Meat yield (% of slaughter weight)	53	51	49	50
Fat yield (% of slaughter weight)	24	26	22	23
Bone yield (% of slaughter weight)	23	23	25	24
Meat moisture (%)	74.3	76.1	77.4	75.5
Meat pH	5.6	5.8	6	5.7

Source: created by the authors

The colour of the meat also varied between groups. Analysis based on the CIELAB standard (L*, a*, b*) showed that lambs from group Ab had meat with the most intense red colour (a* = 13.5). In lambs from group Aa, this indicator was 12.8; in group Aab – 12.1; and in group A(-) – 13.0. These results suggest that the meat from group A(-) lambs had a better visual appearance than that of group Aab, and was comparable in quality to that of group Ab. The most favourable indicators were consistently observed in lambs from Ab dams, confirming their potential for use in breeding programmes aimed at enhancing meat productivity. Lambs from A(-) dams demonstrated results that may be considered competitive, particularly with regard to their meat-to-fat ratio, as well as moisture and pH characteristics. Groups Aa and Aab may require further optimisation of housing and feeding conditions to achieve improved performance.

Discussion

Comparison of the results with previous studies allows for a comprehensive assessment of the importance of maternal genotype for lamb growth and meat production within the context of existing scientific literature. N. Bobokulov *et al.* (2021) established that maternal

genotype is a key factor influencing live weight gain and meat quality in lambs. Their study demonstrated a significant impact on average birth weight, daily weight gain, and weaning weight. The findings of the present study support these conclusions, particularly in showing that lambs born to dams of the Ab genotype exhibited the most favourable growth rates, which aligns with the positive influence of specific genotypes on offspring development noted by N. Bobokulov *et al.* (2021). Other researchers have also highlighted the combined role of genetic and nutritional factors in sustainable lamb production. E. Ponnampalam *et al.* (2020) observed that high maternal lactation levels contribute significantly to improved lamb weight gain. This study confirms that observation, as lambs from Ab dams exhibited the highest average daily gains, reflecting the influence of increased milk yield. Furthermore, this study shows that the maternal genotype has a substantial effect on meat performance: lambs of the Ab group displayed superior slaughter weights and meat quality, further affirming the role of genetic factors in meat production outcomes. These results are consistent with the findings of N. Luthfi *et al.* (2022), who examined the impact of feeding levels on growth and meat quality – research that complements genetic studies by underscoring environmental contributions.

J. Orzuna-Orzuna *et al.* (2021) similarly emphasised that both genetic and environmental variables significantly affect lamb growth and meat characteristics, findings that correspond closely with the results of this study, particularly the performance advantages seen in lambs of the Ab genotype. The study by P. Stapay *et al.* (2023), which explored the biological determinants of sheep meat productivity, also confirms the genetic influence on slaughter weight and meat yield. These conclusions are mirrored in the current findings, where maternal genotype – especially Ab – proved decisive in meat performance indicators. Finally, the article by S. Prache *et al.* (2022) identified genetics and environmental conditions as the principal determinants of meat productivity, particularly in relation to fat content and muscle development. The results of this study reinforce those findings, as the genotype of the dams significantly influenced lamb weight and meat quality traits such as fat and muscle yield. The Ab group again demonstrated the most favourable outcomes, supporting the conclusions drawn in the aforementioned research.

In the study conducted by S. Gallo *et al.* (2019), the effects of various methods of finishing lambs on performance and meat quality were examined. It was established that feeding systems and housing conditions can significantly influence meat characteristics. However, the results also demonstrated that the genotype of the dams plays an equally important role in ensuring optimal growth performance and meat quality in lambs – particularly in terms of higher live weight gain and superior meat traits observed in lambs from dams of the Ab group. This confirms that while feeding systems are crucial, genetic factors may exert an even greater influence on sheep productivity (Daribayeva *et al.*, 2025). In the work of T. Al-Thuwaini (2021), a comprehensive analysis of haematological parameters associated with adaptation and reproduction in sheep was conducted. The author concluded that the general health and physiological adaptation of sheep directly affect their performance. Although these factors were not directly examined in the present study, it is noteworthy that the health status and lactational capacity of the dams significantly influenced lamb growth outcomes. The high milk yield of Ab group dams could be indicative of an optimal physiological state, thereby reaffirming the role of maternal health in achieving high levels of meat productivity (Mukanova *et al.*, 2024). A. Moloney & M. McGee (2023) explored the factors influencing the growth of beef animals, including genetics, housing, and feeding systems. They emphasised the

interaction of these elements in attaining optimal growth and development rates. The findings of the present study support this integrated approach, demonstrating that the genotype of the dams is critical for achieving optimal growth and meat production outcomes – particularly evident in the superior performance of lambs from Ab dams across all major parameters. M. Redoy *et al.* (2020) investigated the effects of herbal supplements on growth, immunity, and meat quality in sheep. They found that such supplements positively impact animal health and productivity. Although the present study did not involve the use of dietary supplements, it is evident that the genetic makeup of the dams had a comparable influence, particularly in maintaining high productivity levels among lambs. This reinforces the importance of genetic factors, which can have an equivalent effect on performance as certain nutritional interventions (Sansyzbayeva *et al.*, 2024).

According to M. Benoit *et al.* (2019), economic and environmental optimisation in livestock production does not always align with the requirements of the meat industry. However, the current study demonstrated that the use of Ab group dams led to high meat yield and lamb productivity, which can simultaneously fulfil both economic and environmental objectives. This highlights the potential of integrating genetic selection strategies into intensive sheep farming systems (Verzhykhovsky & Nedosekov, 2024). Finally, the study by D. Cardoso *et al.* (2021) underscored the significance of nutrition in influencing live weight gain and carcass quality in lambs. The present findings complement this by illustrating the crucial role of dam genotype as an additional determinant. Lambs from Ab dams recorded the highest live weight gains, suggesting a synergistic relationship between nutrition and genetics in optimising lamb performance.

The current study confirms that maternal genotype exerts a significant influence on lamb performance. J. Galaviz-Rodríguez *et al.* (2014) indicated that lamb productivity is shaped not only by genotype but also by production systems. While this study primarily focused on maternal genotype, the results from the Aab group suggest that performance is also dependent on external factors, thereby validating the need to integrate management conditions into breeding strategies. Specifically, the recommendation to improve housing and feeding conditions for dams of the Aab genotype is in line with J. Galaviz-Rodríguez *et al*. (2014) findings on the importance of aligning management systems with genotype-specific requirements.

The study by J. Issakowicz *et al.* (2018) confirmed the effectiveness of crossbreeding in improving productivity. Although crossbreeding was not the focus of the present research, the findings regarding the breeding potential of the Ab genotype align with J. Issakowicz *et al*. (2018) premise that selecting optimal genotypes contributes to enhanced productivity. The high indicators of milk yield, birth weight, and slaughter weight observed in lambs born to Ab dams suggest that further selection based on this genotype may ensure a sustainable increase in productive traits. Early feeding intervention was explored in the study by Y. Paksoy *et al.* (2024), where the authors emphasised the role of early nutritional strategies in promoting lamb growth. Although the present study focused more specifically on maternal genotype, the findings indicate that optimising feeding for genotypes with moderate productivity levels – such as Aa and Aab – could enhance outcomes. In particular, the physiological condition of dams in these groups points to the need for targeted nutritional adjustments to increase their lactation potential. Overall, the findings of this study reaffirm the crucial role of genetic potential in improving sheep productivity, as supported by the cited literature. The Ab genotype emerges as the most promising for breeding programmes due to its consistent milk yield and high fertility, whereas other genotypes may yield improved outcomes under enhanced housing and feeding conditions.

Conclusions

The study of the genotypic structure of mothers according to the A blood group system revealed considerable diversity within the population of the Ascanian fine-wool breed. The most prevalent genotype was A(-), noted for its high adaptability and stable reproductive function. The Ab genotype exhibited the best indicators in terms of milk yield and fertility; the Aa group was characterised by balanced fertility, adaptability, and milk production, while the Aab genotype was marked by high fertility and frequent multiple births. The maternal genotype significantly influenced lamb birth weight, growth rates, daily live weight gains, and weaning weight. The highest productivity indicators were observed in lambs born to mothers of the Ab group, which achieved the greatest birth weight (4.2 kg), highest daily gain (180 g), and maximum weaning weight (18.2 kg). These findings reflect the strong lactation potential and favourable physiological status of dams in this group. Lambs from Aa and Aab dams showed slightly lower indicators, likely due to moderate lactation capacity and the prevalence of multiple births, respectively. In the A(-) group, lambs exhibited the lowest growth rates, although the resilience and adaptability of these dams may partially compensate for these limitations.

The evaluation of maternal genotype effects on meat productivity in lambs at seven months of age demonstrated a clear dependence on genotype group. The highest slaughter weight (21.4 kg) was recorded in lambs from Ab dams, aligning with their superior birth weight and maternal milk yield. Lambs from the Aa group (20.1 kg) also performed well, albeit below that of Ab. Groups A(-) (19.8 kg) and Aab (19.3 kg) yielded lower results, likely due to reduced birth weight, frequent multiple births, and constrained intrauterine development. Maternal genotype also affected meat, fat, and bone yields. The highest meat yield (53%) was observed in group Ab, supporting the notion of optimal muscle development. Group Aa followed with 51%, while groups A(-) and Aab showed 50% and 49%, respectively. The highest fat yield was noted in group Aa (26%), while the lowest was in group Aab (22%), indicating a greater fat accumulation capacity in group Aa. Overall, maternal genotype is a critical factor in determining lamb meat productivity. The Ab genotype emerges as the most promising for breeding purposes, whereas the Aa and A(-) genotypes produce favourable results under well-managed rearing conditions. The Aab genotype would benefit from improved husbandry practices to enhance productivity outcomes. A limitation of this study lies in the absence of long-term observations on how maternal genotype influences the subsequent productivity of lambs under varied rearing and feeding conditions. Furthermore, the study does not address the potential influence of epigenetic factors that may modulate the expression of genetic traits in future generations. Further research could incorporate environmental management systems and early interventions to optimise the productivity of different genotypes.

Acknowledgements

None.

Funding

None.

Conflict of Interest

The authors declare no conflict of interest.

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Ріст і м'ясна продуктивність ягнят залежно від генотипу за показниками системи А груп крові їхніх матерів

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Анотація. Асканійська тонкорунна порода овець є однією з порід, що поєднує високу м'ясну та вовнову продуктивність зі здатністю адаптуватися до умов степових районів, що робить

її перспективним об'єктом для селекційних досліджень. Метою роботи було встановлення залежності між генотиповими характеристиками матерів і основними показниками продуктивності ягнят для підвищення ефективності селекційної роботи. Дослідження проводилося впродовж 2022-2024 років на базі Навчально-науково-практичного центру Миколаївського національного аграрного університету (Україна). До вибірки включали 60 клінічно здорових маток овець асканійської тонкорунної породи віком від 2 до 5 років, які утримувалися в однакових умовах, з мінімальною плодючістю та відсутністю спадкових патологій. Виявлено, що найпоширенішим генотипом серед маток був A(-), який забезпечував стабільну репродуктивну функцію, тоді як генотип Ab продемонстрував найкращі результати молочності та плодючості. Генотип Aa мав збалансовані характеристики, а Aab вирізнявся високою плодючістю з багатоплідними окотами. Ягнята від маток групи Ab мали найвищу середню масу при народженні (4,2 кг), максимальний щоденний приріст (180 г) і найвищу масу при відлученні (18,2 кг). Найнижчі показники спостерігалися у групи A(-), проте ця група демонструвала високі адаптивні властивості. Дослідження м'ясної продуктивності в семимісячному віці показало, що ягнята від маток групи Ab мали найвищу забійну масу (21,4 кг) і максимальний вихід м'яса (53 %), тоді як групи Aa, A(-) та Aab поступалися цими показниками. Генотип матерів впливав також на вміст жиру, кісток і якість м'яса. Висновки підтвердили, що генотип матерів значною мірою визначає продуктивність ягнят, причому найвищі показники зростання, молочності та м'ясної продуктивності продемонстрував генотип Ab, що підтверджує його перспективність для селекційної роботи

Ключові слова: селекція; забійна маса; плодючість; молочність овець; асканійська тонкорунна порода

ANIMAL SCIENCE AND FOOD TECHNOLOGY

Journal homepage: https://animalscience.com.ua/en
Animal Science and Food Technology, 16(2), 39-54
Received 25.12.2024 Revised 20.04.2025 Accepted 22.05.2025

UDC 664.292
DOI: 10.31548/animal.2.2025.39

Evaluation of technological parameters of convective drying of pumpkin seeds with vibro-ozonation intensification of the process

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Abstract. Thermal and mechanical effects commonly pose challenges during the heat and mass transfer treatment of seed products. Consequently, drying methods utilising a vibratory fluidised bed, which minimise these effects on plant-based products, remain relevant. This study aimed to enhance the driving force and, consequently, the efficiency of the dehumidification process for thermolabile plant raw materials by employing vibro-mechanical activation of seed material movement, increasing electro-osmotic pressure to improve moisture diffusion conditions, and achieving disinfection during processing. The research methodology included experimental investigations conducted using a vibratory bed system with an ozone-air drying agent. The study examined the influence of vibration frequency, ozone concentration, and temperature regime

Suggested Citation:
Palamarchuk, I., Mushtruk, M., & Mushtruk, N. (2025). Evaluation of technological parameters of convective drying of pumpkin seeds with vibro-ozonation intensification of the process. *Animal Science and Food Technology*, 16(2), 39-54. doi: 10.31548/animal.2.2025.39.

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on drying kinetics, heat and mass transfer rates, disinfection levels, and energy efficiency. Based on the results, a process flow diagram for convective drying of grain and cereal materials was developed, incorporating vibratory and ozonising means to intensify the process. The proposed process flow diagram ensured the necessary disinfection of the product, improved heat transfer conditions, maintained consistent hydraulic resistance along the entire rarefaction chamber, and ensured uniform drying. It also reduced energy consumption, enhanced the durability, reliability, and productivity of the process, and prevented overheating of the material, thereby enabling the drying of thermolabile products. Research findings demonstrated that filtration drying with vibro-ozonation reduced the processing time for pumpkin seeds by a factor of 1.67 and decreased energy consumption by a factor of 1.71 compared to conventional convective methods. The highest drying rate was achieved with filtration vibratory drying, which proved to be 1.68 times more efficient than convective drying. The practical significance of this research lies in the development of drying equipment that ensures uniform drying, mitigates the risk of overheating, and improves the longevity and productivity of the process. The obtained results can be implemented in industrial settings for the efficient processing of thermolabile agricultural products

Keywords: dehumidification processes; ozone; vibration; fluidised bed; heat carrier; thermolabile products; heat and mass transfer processes

Introduction

In modern drying technologies, vibration methods of technological impact on plant raw materials are becoming increasingly in demand in the processes of food and processing industries due to factors such as increased equipment productivity, shortened production cycles, and improved product quality; intensification of heat and mass transfer processes. W. Zhang *et al.* (2021) proved the feasibility of such technological measures in the processes of dehumidification and drying of seed and fruit-vegetable material. When creating low-frequency vibrations in a bulk mass of the product, the adhesion between the particles of the technological load weakens, which leads to the emergence of a fluidisation state in the system. In the research of I. Palamarchuk *et al*. (2023), it was proved that such a state of the processed medium contributes to the effective mixing of the mass due to an increase in the contact interaction area. At the same time, this allows for a reduction in the cost of bubbling the heat carrier through the material flow, since the magnitude of internal friction decreases.

An interesting aspect is the development of combined physical-mechanical and vibrational methods for moisture removal from raw materials in the food and processing industries. In the scientific studies of M. Mohamed *et al*. (2021), the main characteristics of vibrational electro-osmotic dehumidification of pectin-rich food raw materials, particularly beet pulp, were investigated. The authors proved that it is possible to increase the driving force of the dehumidification process by applying centrifugation with rotor rotation, superimposing lowfrequency vibrations on the working container, creating an electro-osmotic effect under conditions of one-sided diffusion, and filtering the medium through perforations in the rotor.

Research by M. Capece & J. Larson (2022) established that the combination of these physicomechanical factors in the dehumidification process significantly enhances technical and economic parameters. Specifically, the specific energy consumption for removing 1 kg of moisture is reduced by a factor of 2.7 compared to traditional convective drying. Thus,

the proposed processes and equipment facilitate the intensification of dehydration and improve the efficiency of production technologies. I. Rogovskii *et al*. (2020) demonstrated that the application of wave and pneumodynamic processes for treating grain and cereal products substantially enhances the contact interaction between the product and the air environment. These technological approaches create favourable conditions for storage operations, optimise the microclimate in grain storage facilities, and promote intensive agitation of bulk material masses. The implementation of such methods was found to significantly improve the quality of stored products by ensuring uniform moisture distribution and reducing the risk of adverse processes in grain storage, such as the formation of stagnant zones or overheating.

Research by A. Tuncer *et al.* (2020) has established that the process of drying pumpkin seeds using an ozone-air mixture has a dual technological effect. In the initial drying period, ozone enters into oxidation reactions on the surface of the grain with organic and inorganic substances, providing a cleaning effect on the surface of the grain material. At the same time, part of the surface moisture interacts with the formed ozonides, which further intensifies the moisture removal process. As noted by D. Delfiya *et al*. (2021), the ozone-air mixture, used as a drying agent, not only contributes to reducing moisture but also provides a disinfecting effect on the surface microflora due to the reactive action of ozone. The effectiveness of this effect depends on the ozone concentration and the drying temperature regime, which underlines the importance of precise control of these parameters in the technological process.

According to the research of D. Wang *et al.* (2021), the application of vibration technologies contributes to the optimisation of technological processes, particularly through reduced energy consumption, which is an important aspect in the context of current trends towards energy efficiency and rational resource use. The authors claim that their application allows for the efficient execution of dehumidification, drying, mixing, and separation processes with minimal heat losses and significantly lower energy costs. Such an approach contributes not only to reducing production costs but also to increasing the competitiveness of the final product on the market. Vibrational processes ensure uniform processing of materials, making them promising for widespread implementation in the food and processing industries.

One of the significant advantages of modern technologies is their environmental friendliness. As noted by S. Şevik *et al.* (2019), the use of an ozone-air mixture for drying pumpkin seeds provides a high level of disinfection without the need for chemical preservatives. Research results have shown that ozone, as a powerful oxidant, effectively destroys the cells of bacteria, fungi, and other microorganisms, while preserving the natural properties of the product. Such an approach is particularly important in the production of organic products, where minimising the use of chemical additives is a top priority. Thanks to this, the ozonation method is finding increasingly widespread application, combining effective treatment with environmental safety.

The combination of these advantages makes vibration technologies an important component of modern production processes in the food and processing industries. Their widespread implementation not only improves the quality and safety of food products but also makes the production process more environmentally sustainable and economically viable. Thus, vibration technologies represent a promising direction for research and implementation in industries focused on innovation, efficiency, and environmental responsibility. The aim of the presented scientific research was to increase the productivity of the pumpkin seed dehumidification process and to improve its technological qualities through the use of mechanical vibrations to increase the contact area

with the heat carrier flow, activate electro-osmotic diffusion of moisture, and disinfect the plant product with ozone.

Literature Review

The development of energy-efficient and high-quality methods for drying biological materials occupies a leading place in modern scientific research due to the need to ensure high productivity and minimise the loss of nutrients. One of the promising directions is the application of low-frequency vibrations, which create additional mechanical heat and mass transfer effects. R. Gomez *et al.* (2023) noted that the creation of a vibrated fluidised bed not only increases the total contact area between the bulk material and the drying agent but also contributes to a uniform temperature distribution throughout the volume of the material. In their experiments, the authors showed that at optimal parameters (vibration amplitude 1.5-2 mm, frequency 50-60 Hz), there is a significant reduction in drying time while maintaining quality indicators. The research of Á. Calín-Sánchez *et al.* (2020) covered the features of drying vegetables in a vibrated fluidised bed with additional radiant heating. The authors established that the combined use of methods allows for reducing heat losses due to more effective penetration of heat into the material. This ensures not only the preservation of nutritional properties but also a significant reduction in energy consumption.

In the study of R. Ilyas *et al.* (2019), the processes of sugar crystallisation under various vibration frequencies were analysed in detail. In particular, it was established that at frequencies of 30-70 Hz, crystallisation accelerates by 2.5-9 times, which is explained by the activation of internal moisture transfer in the material. The author emphasised the need for optimal coordination of the frequency and amplitude of vibrations to minimise energy consumption. R. Aslam *et al.* (2021) investigated the influence of alternating dynamic loads on the rheological properties of beet pulp. The results showed that with an increase in the shear rate, the viscosity of the process mass decreases significantly, which, in turn, contributes to the faster removal of moisture through capillaries and pores. The author's contribution also includes the development of mathematical models for predicting these processes in real production conditions.

L. Bal-Prylypko *et al.* (2022) in their scientific article argue that vibrational impact during the drying of granulated sugar in a vibrated fluidised bed allows reducing the time required to transition to the period of falling drying rate. The authors' experiments also showed that the maximum intensity of the process is observed at an amplitude of 2 mm and a frequency of 50 Hz. S. Moscatello *et al.* (2023) and V. Vasyliv *et al.* (2021) investigated the effectiveness of lowfrequency vibrations in the second period of beet pulp drying and found that additional mechanical impact during this period allows avoiding the formation of excessively dried zones, which ensures uniform quality of the final product.

I. Palamarchuk *et al.* (2023) made a significant contribution to the development of equipment for drying bulk materials, creating a series of installations for vibro-filtration drying. The authors described in detail its operating principle, noting that although it provides a high level of productivity, its complex design can lead to excessive energy consumption and non-uniform drying due to the hydraulic resistance of the layer. I. Rogovskii *et al.* (2020) developed a dryer for grain and oilseed crops, which includes a labyrinthine working zone. The authors proved that such a design contributes to improving the movement of the drying agent through the material layer. However, they noted that the single use of the drying agent and difficulties in regulating the modes limit the potential of this technology.

Convective dryers are one of the most common for processing bulk materials. To improve them, rotary dryers were developed, which

allow for effective mixing of the material, ensuring uniform drying. For example, researchers such as Y. Li *et al.* (2022) and others studied the influence of rotation speed and blade design. In addition, dryers with a fluidised bed have been developed, which provide high heat and mass transfer efficiency. Infrared dryers allow for reducing drying time and energy consumption. It was important to develop combined systems that combine infrared radiation with convective heating. Scientific works, for example, by D. Huang *et al.* (2021), are aimed at modelling the energy distribution in the infrared field.

Microwave drying provides rapid heating due to the penetration of energy deep into the material. One innovation is the combination of microwave drying with vacuum technologies, which minimises thermal loading. Engineers from the Institute of Engineering Thermophysics of the National Academy of Sciences of Ukraine have worked in this direction. Vibrational dryers intensify the drying process due to the mixing of particles, preventing the formation of zones with reduced heat transfer. Vibro-ozonation technologies, proposed in the research of A. Niveditha *et al.* (2021), allow for the treatment of materials not only by drying but also by the oxidation of microorganisms. The introduction of electro-osmosis allows for reducing moisture in capillaryporous materials by creating an electric field. Research in this direction is actively conducted in EU countries, as well as in Ukraine, particularly at the Institute of Biosystems Energy.

Combining different methods (such as convective, infrared, and microwave drying) allows for achieving a synergistic effect. Scientists D. Elustondo *et al.* (2023), M. Awad *et al.* (2024), and Y. Mao & S. Wang (2023) demonstrate the latest achievements in the field of dryer design. For example, dryers with adaptive control involve the use of artificial intelligence systems and sensors to optimise the process in real-time. Energy recovery drying units use the heat of the exhaust air to preheat new batches of material. Compact mobile dryers are designed for local use, especially in agricultural cooperatives.

The future of equipment for drying bulk materials is linked to the development of environmentally friendly technologies with minimal impact on the environment; technologies focused on reducing energy consumption; and universal dryers capable of adapting to different materials and conditions. These works not only reveal the mechanisms of heat and mass transfer processes but also open up new perspectives for the integration of vibration and ozonation methods on an industrial scale. In the future, special attention should be paid to combining energy-efficient technologies with ensuring the quality of the finished product.

Materials and Methods

Moisture measurement of pumpkin seeds being dehydrated in a drying chamber was carried out using an indirect method, taking into account the ability of the drying agent to absorb moisture when passing through a layer of product, leading to a change in its relative humidity. Knowing the initial moisture content of the product, the relative humidity of the drying agent at the inlet and outlet of the drying chamber, as well as the flow rate of the drying agent, the moisture content was determined using H-d diagrams, where H is the enthalpy of atmospheric air (in kJ/kg of dry air), and d is the moisture content of the air (in %).

The flow rate of the drying agent was calculated using the formula (1):

$$L = 3{,}600 \cdot \gamma \cdot v \cdot F, \quad (1)$$

where L is the flow rate of the drying agent, kg/h; γ and v are the density (in kg/m^3) and velocity (in m/s) of the drying agent, which depends on the moisture content and barometric pressure in the air duct; F is the cross-sectional area of the air duct, m^2.

The density of the drying agent was determined from the relationship (2):

$\gamma = 2 \cdot 10\text{-}3 \cdot (B/(273+t)) \cdot ((1{,}000+d)/(622+d))$, (2)

where B is the barometric pressure, *Pa*; t is the temperature of the drying agent, *°C*; is the moisture content of the drying agent, *g/kg*.

The velocity of the drying agent was determined using a vane anemometer. The measurement of the relative humidity of gases is traditionally carried out using psychrometers, the main components of which are dry and wet thermometers. To measure and regulate the parameters of the studied heat and mass transfer processes, ensuring guaranteed compliance with the parameters of the intensive drying process of pumpkin seeds with vibro-ozonation activation, a design, software, and a microcontroller system were developed and manufactured (Fig. 1).

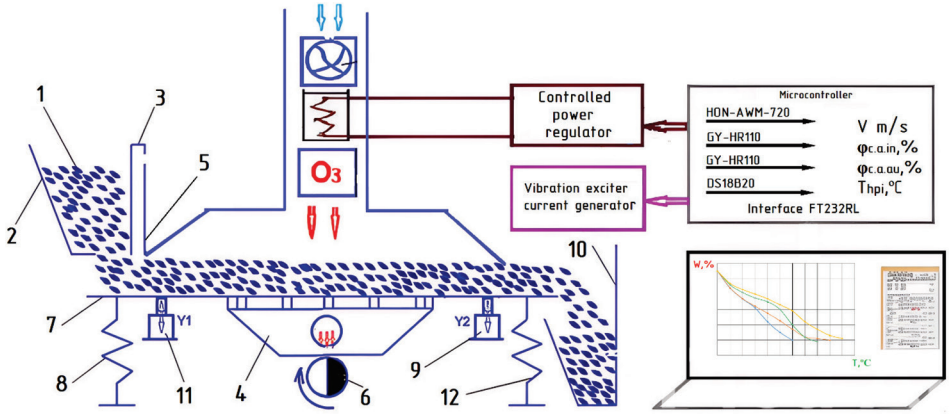

Figure 1. Installation for drying bulk materials with vibro-ozonation technological impact and a system for adaptive control of the dehydration process

Source: authors' development

The developed system allowed for the determination of the temperature and humidity of the heat carrier, as well as the velocity of the drying agent. This enabled the calculation of its flow rate and, consequently, the acquisition of comprehensive data for the continuous calculation of the moisture content of the seeds within the drying chamber. The equipment also functioned as a timer, automatically recording the current temperature and humidity data. This enabled the presetting and recording of time stamps with an accuracy of one minute. The data and control point memory were, however, power-dependent. The accumulated and current information about the dehydration process parameters was transmitted to a computer via an interface for further analysis, processing, and calculation. When connected to a computer, the microcontroller's clock was automatically synchronised with the computer's clock.

The calculation of the current moisture content of the product was performed using a computer and the given formulas (1) and (2), utilising the moisture content values of the drying agent obtained from the microcontroller and the input constants characterising the process. The research involved considering the following technological impacts on pumpkin seeds: filtration drying with vibro-ozonation activation; filtration heat exchange with vibration activation; filtration drying itself; and convective drying of the product in a stationary state. To implement these technological measures, an experimental setup was developed, the scheme of which is presented in Figure 1.

The experimental setup consists of a hopper 2 (Fig. 1) on which gate 3 is placed to regulate the height of the layer of wet material 1. Below hopper 2, there is a vacuum chamber 4 connected to a vibration exciter 6, on which a perforated bottom of the working chamber 7 is fixed. The latter is installed on elastic supports 8 and 9. Below the bottom 7, two symmetrically placed variable-angle electromagnets 11 and 12 are mounted. A drying chamber 5 is installed above the vacuum chamber, with an unloading hopper 10 located in its lower part.

During the operation of the experimental model, a heating agent is supplied to the drying chamber 5. From hopper 2, using slide gate 3, the wet material 1 enters the upper part of the perforated bottom 7 and moves along its surface under the action of low-frequency vibrations generated by the vibration exciter 6 in the direction of the unloading hopper 10. Due to the created vacuum in chamber 4, the heating agent is filtered through a layer of wet material, which, due to intensive mixing under conditions of low-frequency vibrations, has high porosity and, accordingly, low hydraulic resistance, which allows for a significant intensification of the drying process and a reduction in energy consumption.

Results and Discussion

The mechanism of the investigated process of convective drying with vibro-ozonation activation occurs as follows. When ozone is directed onto the surface of plant material, free radical processes arise, which rapidly spread into the internal tissues. In essence, this amounts to the transfer of energy, which is released at the molecular levels of the upper layer of the grain or food product, into the internal tissues. Moreover, part of the excess energy is spent on physicochemical transformations, as a result of which the structure of cell membranes, redox potential, ionic permeability, and other cell properties change. Part of the energy is converted into heat, accelerating the development of the studied heat and mass transfer processes of dehumidification.

As ozone passes through the grain mass, it decomposes into molecular and atomic elements, O_2 and O, releasing heat equivalent to 142 kJ/mol. Atomic oxygen binds moisture around itself in the form of droplets, which are carried away by the airflow. After the removal of surface moisture, ozone affects the permeability of cell membranes, and the presence of atomic oxygen promotes the movement of moisture outwards. The next stage of drying involves the removal of sorption-bound moisture, using the amount of heat released during the decomposition of ozone, as well as the presence of atomic oxygen and ions of different polarities. Under the influence of electromagnetic interaction forces, the dipole bonds of water molecules with the pumpkin seed cells are weakened, which significantly affects the increase in the drying rate of the grain during this period. The introduction of low-frequency vibrations into the technological mass of the product ensures both an increase in the contact area between the material and the heat carrier flow and an improvement in the efficiency of the aforementioned chemical interaction reactions.

In the investigated process, using the aforementioned technological methods, an evaluation was conducted based on parameters such as seed moisture content, moisture removal rate, and temperature of the pumpkin seed material, which can be explained by the peculiarities of the physicochemical processes occurring within the seed and its shell (surface) and the seed mass itself (Fig. 2).

At the initial stage (moisture content of 54-30%), the mixing effect was uneven due to the sticking of seeds to each other and to equipment parts. Partially due to the formation of a crust, the transparency of the perforated bottom was impaired, which hindered the supply of the drying agent. Therefore, heating of the seed mass occurred gradually, mainly due to conductive heat transfer. The moisture removal

process was ensured by the evaporation of free moisture from the seed surface and the filtration of unbound surface moisture in the direction of natural flow "seed layer – perforated bottom". The pressure difference was found to be excessive above the seed layer due to the injection of heated and ozone-enriched drying agents and the rarefaction in the sump-diffuser space, which significantly activates the dehydration process at relatively low temperatures.

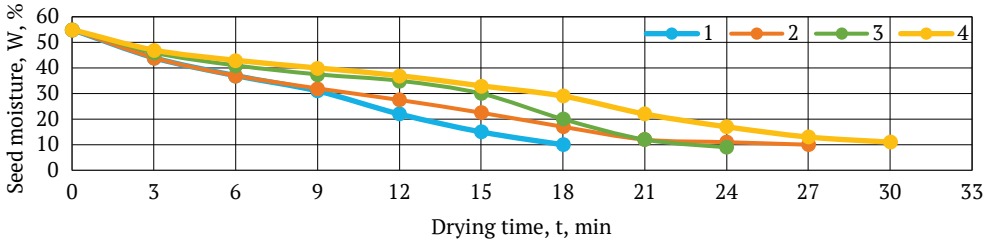

Figure 2. Dependence of pumpkin seed moisture content W, % on drying time τ (in min) for different drying methods

Note: 1 – filtration with vibro-ozonation activation; 2 – filtration with vibration activation; 3 – filtration; 4 – convective in a stationary bed. The drying agent temperature for the pumpkin seed moisture content range of 54-35% was 30°C and within the range of 35-10% – 50°C

Source: authors' development

The next stage of moisture removal (moisture content of 30-15%) is characterised by a deterioration of the adhesive and cohesive properties of the seeds, which contributed to the activation of the mixing process, forming "fountaining" areas. The continuous film of moisture is removed, and the liquid phase moves from the pores and capillaries of the shell to the outer surface of the seed, from which it evaporates. Moreover, voids free of liquid phase are created and spread within the shell. Moisture is also transferred from the seed surface by concentration diffusion. Due to the increased influence of the convective component, an increase in the temperature of the seed mass is observed. The results of studies determining the effect of the drying agent temperature on the heating of the core and shell of pumpkin seeds with changes in seed moisture content are shown in Figures 2 and 3.

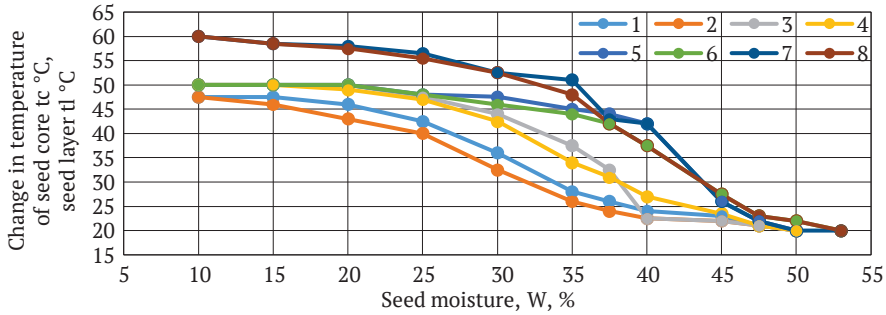

Figure 3. Changes in the temperature of the seed kernel (embryo) t_k (°C), seed coat t_c (°C) during filtration drying of pumpkin seeds at different seed moisture content values W, % and drying agent temperature

Note: at (W < 38%): Tda_{1f} – 30°C; Tda_{2f} – 40°C; Tda_{3f} – 50°C; Tda_{4f} – 50°C; at (W > 38%): Tda_{1c} – 50°C; Tda_{2c} – 50°C; Tda_{3c} – 50°C; Tda_{4c} – 60°C

Source: authors' development

The final stage of drying (seed moisture content 17-8%) occurred in a mode of active mixing in a vibrofluidised bed, facilitated by a significant mass loss and cleaning of the seed surface. The moisture transfer mechanism is characterised by a deepening of the evaporation front into the seed kernel. Swelling moisture, as well as condensation from the surface of the kernel, moves through the developed system of capillaries and pores of the coat and evaporates at the phase transition boundary. Further, the phase transition front moves into the depth of the kernel, and moisture enters the coat in the form of vapour. This stage is characterised by significant heating of the seed mass due to intensive exchange of its surface and contact with the drying agent. At values of $Tda_{4f} > 50°C$, a crust is formed in the layer of pumpkin seed moisture, making the seed layer virtually impermeable to the filtration of the drying agent. Therefore, studies in mode No. 4 were conducted at $Tda_{4f} - 50°C$ (Fig. 4).

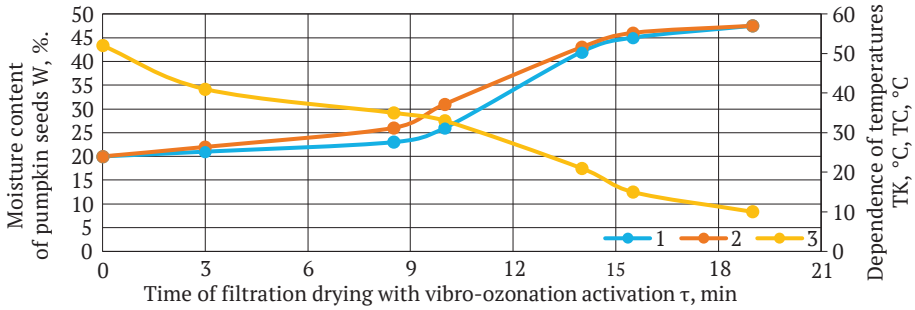

Figure 4. Dependence of the seed kernel temperature TC, °C (line 1), pumpkin seed moisture content W, % (line 2), and seed coat temperature TC, °C (line 3) on the filtration drying time with vibro-ozonation activation τ (in min)

Source: authors' development

Results of studies on the heating of the seed kernel (embryo) and the outer seed coat, depending on the drying agent temperature, allowed the determination of the maximum permissible temperatures at which the seed's conditioning characteristics, in particular its germination and germination energy, are preserved. According to the obtained data, the maximum heating temperature of the protein components of the embryo should not exceed $t_k = 42°C$ to ensure optimal germination and germination energy indicators. In cases where the temperature of the drying agent exceeds t_c, the maximum permissible temperatures for maintaining sowing qualities are 47°C and $t_{da} = 50°C$ at a specific energy consumption of $Q = 4.23$ MJ/kg of relative humidity. Thus, the conducted studies allow for a clear definition of temperature limits for safe drying, taking into account the quality of the seeds and the energy efficiency of the process.

To optimise the technological and energy parameters of vibro-ozonation drying of pumpkin seeds in a vibrofluidised bed, a comparative analysis of the efficiency of drying processes carried out using the developed microcontroller system was performed (Fig. 2, 3, 4, 5). According to the experimental results, the use of the latest system allowed for a significant improvement in drying parameters compared to traditional methods. In particular, the increase in drying rate was from 1.12 to 1.68 times, indicating a significant increase in process efficiency. Specific energy consumption decreased by 1.21-1.71 times, and processing time decreased by 1.21-1.67 times, which significantly reduces energy costs and increases drying productivity.

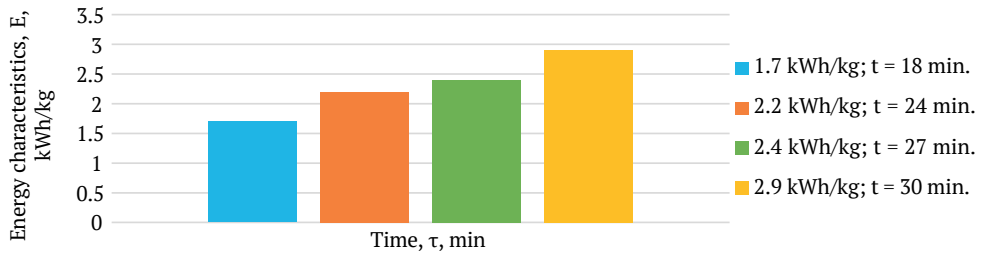

Figure 5. Energy characteristics of the studied convective methods of drying pumpkin seeds
Note: 1 – filtration with vibro-ozonation activation; 2 – filtration with vibration activation; 3 – filtration; 4 – convective in a static product bed. The drying agent temperature for the product moisture content range of 54-35% was 30°C and within the range of 35-10% – 50°C
Source: authors' development

Particularly high results were achieved using filtration drying with vibro-ozonation activation, which demonstrated the highest efficiency in reducing seed processing time and energy consumption. This phenomenon is explained by a significant decrease in internal friction within the seed mass and a significant increase in the contact area between the seeds and the heat carrier. Such improvement allows for a significant acceleration of the drying process due to more intensive heat transfer, which in turn contributes to a decrease in energy consumption. In particular, the highest drying rate was recorded for filtration vibration drying (Fig. 5), which confirms its high efficiency compared to other methods.

Filtration drying with vibro-ozonation activation showed the best characteristics in minimising the processing time of pumpkin seeds and energy consumption for the process, which is explained by the greatest reduction in internal friction in the product mass and the largest contact area of seed coverage by the heat carrier flow. The highest drying rate was observed for filtration vibration drying (Fig. 5).

The conducted research demonstrates that the experimental model of a convective dryer with vibro-ozonation intensification has a significant advantage in terms of pumpkin seed drying efficiency. The intensive mixing of seeds during heat transfer results in rapid and uniform drying of the material. In particular, traditional drying systems often face the problem of uneven heating: the seed surface may experience overheating, while the inner layers remain moist (Carter *et al.*, 2019). Such uneven drying leads to a decrease in the quality of the finished product and increases the overall processing time.

In the investigated model, vibratory mixing of the seeds allows for avoiding such problems, which is extremely important when processing seeds with a high moisture content at the initial stages of drying. For example, for sunflower seeds, which often require prolonged drying due to a thick husk, vibration technologies could also increase drying efficiency and allow for better preservation of nutrients, which is important for the food industry. Periodic drying methods, described in the research of N. Langenaeken *et al.* (2019), are characterised by the fact that the entire volume of seeds is processed simultaneously and remains stationary in the dryer until the process is complete, while the flow regime provides faster and more uniform moisture removal. Unlike such technology, the developed flow process ensures continuous movement of the seeds through the drying chamber. The ability to adjust the residence time of the seeds in the drying chamber allows the process to be adjusted according to the specific characteristics of the material.

In the developments of L. Roy *et al.* (2020), it was proven that a continuous process also

contributes to reducing equipment setup losses between batches, which is an advantage for mass production, where minimising downtime and cooling periods between batches is critical. For the proposed model, more humid or more heat-sensitive types of seeds may require a longer stay at lower temperatures, which is easily achieved in the proposed model.

To ensure the economic feasibility of drying and dehumidification processes in large enterprises, there is a growing demand for simple convective technologies (Sá-Caputo *et al.*, 2019). At the same time, every percentage of energy consumption significantly affects the final cost of the product, therefore, the introduction of vibration-filtration dryers will reduce costs and, accordingly, increase the competitiveness of products on the market. Filtration drying with vibro-ozonation activation has shown that overall energy consumption can be reduced by 1.71 times compared to the traditional convective drying method.

For small farms, the issue of ensuring minimal heat treatment duration is relevant both to save energy costs and to improve product quality and, consequently, demand for it; this requires increasing the drying rate of seeds before long-term storage and allows for significant time savings at a high processing rate without loss of product quality (Piddubnyi *et al.*, 2024). In this regard, the studied vibro-ozonation activation contributes to reducing internal friction between seed particles, which significantly improves heat and mass transfer conditions. Such an approach contributes to the rapid heating of the material with minimal heat consumption for the "internal" processing of the product, which explains the significant energy savings. According to the research results, filtration vibration drying showed a process speed that exceeds the traditional convective method by 1.68 times. Fast drying provides an increase in the number of batches processed in one cycle of the dryer operation, which leads to an increase in the productivity of production capacities.

The quality of the final product is a crucial indicator of drying efficiency, especially when it comes to food products. In traditional methods, where there is no active mixing, seed particles may be heated unevenly, leading to so-called "overheating" in the contact zone with the heat carrier; for example, when drying corn or wheat, overheating of the grain can cause damage to the outer coat, which impairs its germination during subsequent sowing, according to research (Akhlaq & Ali, 2020). The application of vibro-ozonation activation has made it possible to achieve a uniform temperature regime throughout the entire volume of the drying chamber, which minimises thermal and mechanical damage to the product structure and loss of its nutritional properties. Thanks to uniform mixing and gradual renewal of the moisture exchange surface, the proposed technology avoids such problems, preserving the integrity and quality of the seeds.

Heat treatment of plant raw materials in a static bed within stationary thermal chambers or cabinets requires a sufficiently high energy consumption to achieve an acceptable result, which is usually accompanied by significant heat losses (Sun & Seok, 2019; Singh & Agarwal, 2021). With such drying methods, the contact of seeds with the heat carrier is limited, which is why seed particles must be overheated to ensure effective heat and mass transfer (Wang *et al.*, 2020). When using the investigated model of a vibroconvective dryer with a fluidised bed of the product, under conditions of active surface renewal, it is possible to achieve the best results even at lower temperatures of the heat carrier, which also contributes to preserving quality.

In the production of organic products, preserving the biochemical properties of the material under convective heat exchange conditions is a significant challenge (Wathelet *et al.*, 2020). The proposed technology has significant potential for this industrial application, as it combines economic efficiency and high

drying speed with product quality preservation. Reduced energy consumption also has a positive impact on the environmental performance of production, as heat energy consumption is directly correlated with the level of emissions into the environment. The implementation of such technology in industrial lines would contribute not only to resource savings but also to reducing the overall environmental impact of production, which is an important factor in modern society.

In summary, the developed method of convective drying with vibro-ozonation intensification demonstrates several significant advantages over traditional methods. It provides a high speed of seed processing with a significant reduction in energy consumption, making it economically viable and environmentally sound. The uniformity of the temperature distribution, the ability to adjust the process parameters, the high quality of the final product, and the reduction of the negative impact on the environment make the proposed methodology attractive for implementation on an industrial scale.

Conclusions

As a result of the conducted scientific research, a design, software, and a microcontroller-based complex were developed for remote monitoring and computer interpretation of data with adaptive temperature control of thermolabile seed materials, namely pumpkin; which allowed measuring the temperature and humidity of the heat carrier, the speed of the drying agent, and indirectly – carrying out the current calculation of seed moisture, monitoring the heat and mass transfer process with the determination of rational process parameters.

The results of the studies conducted using the developed experimental model of a convective dryer with vibro-ozonation intensification of the seed processing process showed the following advantages of the proposed method: intensive mixing of seeds during heat transfer; continuous flow moisture removal process; the ability to adjust the residence time of seeds in the drying chamber; equalisation of the material temperature throughout the entire volume of the drying chamber; intensive moisture removal with constant renewal of the moisture exchange surface; carrying out the process under rational regimes that ensure the current requirements for the final quality of the material and a significant reduction in specific energy consumption.

Filtration drying with vibro-ozonation activation demonstrated the best characteristics in minimising the processing time of pumpkin seeds: a 1.67-fold decrease compared to the convective heat transfer method and a 1.71-fold decrease in energy consumption for the process compared to traditional convective drying, which is explained by the greatest reduction in internal friction in the product mass and the largest contact area of the seed coverage with the heat carrier flow. The highest drying rate was shown for filtration vibration drying, which exceeded this indicator in the case of the convective method of processing by 1.68 times.

Promising directions for improving the studied technologies may include the use of vibrators with kinematic combined vibration excitation, which will significantly reduce the vibrating mass and, accordingly, energy consumption for the process; the implementation of a vibro-wave conveyor system, which makes it possible to both reduce energy consumption and metal consumption of drying equipment while maintaining the quality effects of the proposed technology.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

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Оцінка технологічних параметрів конвективного сушіння насіння гарбуза з віброозонуючою інтенсифікацією процесу

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Анотація. У процесі тепломасообмінної обробки насіннєвої продукції, як правило, виникають проблеми відносно наслідків термічної та механічної дії. Тому застосування методів сушіння з вібророзрідженим шаром продукції, що дозволяє мінімізувати механічний та термічний вплив на рослинну продукцію, не втрачають актуальності. Метою даної наукової роботи стало підвищення рушійної сили та відповідно ефективності процесу зневоложення термолабільної рослинної сировини за рахунок застосування вібромеханічної активації руху насіннєвого матеріалу, підвищення електроосмотичного тиску для поліпшення умов дифузії вологи, реалізація дезінфективного впливу у процесі обробки. Методологія дослідження включала експериментальні дослідження в установці з вібраційним шаром і озоно-повітряним сушильним агентом. Досліджували вплив частоти вібрацій, концентрації озону та температурного режиму на кінетику сушіння, швидкість тепломасообміну, рівень дезінфекції та енергоефективність. За результатами дослідження розроблена схема конвективного сушіння зернового та зерно-круп'яного матеріалів з вібраційними та озонуючими засобами його інтенсифікації. Запропонована схема дозволила забезпечити необхідну дезінфекцію продукції, поліпшити умови теплопередачі; забезпечити однаковий гідравлічний опір вздовж всієї камери розрідження, рівномірність сушіння; зменшення енергетичних витрат на процес, збільшення його довговічності, надійності та продуктивності; виключення перегріву висушуваного матеріалу, що зробило можливим здійснювати процес сушіння термолабільної продукції. За результатами досліджень доведено, що фільтраційне сушіння з віброозонуванням скорочувало час обробки насіння гарбуза в 1,67 раза, зменшуючи енерговитрати в 1,71 раза порівняно з традиційним конвективним методом. Найвища швидкість сушіння була досягнута при фільтраційному вібраційному сушінні, яке виявилося ефективнішим за конвективне в 1,68 раза. Практична цінність роботи полягає у розробці конструкції сушильного обладнання, що забезпечує рівномірність сушіння, знижує ризик перегріву, підвищує довговічність і продуктивність процесу. Отримані результати можуть бути впроваджені у виробництво для ефективної обробки термолабільної сільськогосподарської продукції

Ключові слова: процеси зневоложення; озон; вібрація; псевдорозріджений шар; теплоносій; термолабільна продукція; процес тепломасообміну

ANIMAL SCIENCE AND FOOD TECHNOLOGY

Journal homepage: https://animalscience.com.ua/en
Animal Science and Food Technology, 16(2), 55-76
Received 06.01.2025 Revised 27.04.2025 Accepted 22.05.2025

UDC 636.5:637.5:613.2:637.514
DOI: 10.31548/animal.2.2025.55

Halal poultry slaughter technology: A critical review of control points

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Suggested Citation:
Mylostyvyi, R., Lykhach, V., Gutyj, B., Marenkov, O., & Mylostyva, D. (2025). Halal poultry slaughter technology: A critical review of control points. *Animal Science and Food Technology*, 16(2), 55-76. doi: 10.31548/animal.2.2025.55.

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Abstract. Halal production holds substantial potential for further development, driven by the growing global demand for high-quality, safe, and ethically produced food products. In addition to meeting the needs of Muslim consumers, certified halal products are increasingly appealing to a broader audience that values compliance with high standards of hygiene, traceability, and quality. Modern trends highlight the importance of adhering to stringent requirements, enhancing the competitiveness of halal production in international markets. This literature review examined the technological process of poultry slaughter with a focus on compliance with halal standards and requirements. The study aimed to identify risks at each stage of production, assess their impact on product quality, and propose strategies to optimise production processes in accordance with Islamic standards. The analysis was based on a review of contemporary scientific literature, certification standards, and risk management practices in food production. Key risks are associated with pre-slaughter inspection, stunning, slaughter, bleeding, evisceration, chilling, and post-mortem inspection. It was found that violations at these stages may lead to mechanical damage to carcasses, insufficient bleeding, microbial contamination, or non-compliance with religious standards. Implementing risk management systems, such as HACCP, and adopting modern traceability technologies, including RFID tags and blockchain, can improve transparency, production efficiency, and compliance with international standards. The value of this study lies in identifying directions for improving process control systems, particularly through the integration of automated solutions for monitoring critical points and analysing product quality. The findings may prove useful for raising awareness about poultry slaughter quality requirements in halal-certified production. Future research prospects include the enhancement of slaughter technologies, the development of automated control systems, and the optimisation of quality assessment methods to improve production efficiency and ensure compliance with high hygienic and religious standards

Keywords: halal production; meat safety and quality; critical control points; risk management; traceability

Introduction

The halal products market is a significant sector of the modern food industry, catering not only to Muslim consumers but also to a broader audience interested in high standards of quality, safety, and ethical production. Products manufactured in compliance with Islamic norms include not only meat products but also a wide range of items, such as cosmetics, pharmaceuticals, and logistics services (Azam & Abdullah, 2020; Hidayat & Musari, 2022). According to M. Gul *et al*. (2023), the halal industry is experiencing significant growth and holds substantial potential for further development. This growth is driven by the increasing global demand for high-quality, safe, and ethically produced food products. Halal certification is increasingly seen as a mark of quality assurance. This positions halal products favourably in both local and international markets, indicating a promising future for the industry. The main idea of the study conducted by M. Asri Abdullah & E. Siddique (2021) is to define "halal entrepreneurship" as a distinct concept from conventional entrepreneurship, highlighting the specific features that characterise entrepreneurs operating within the halal industry, and to explore the diverse business opportunities in the global halal market.

Poultry meat occupies a central position in the halal sector due to its versatility, relatively

low production costs, and compliance with religious requirements. Poultry farming is one of the most dynamic sectors of the agri-food industry, demonstrating stable growth in production and consumption. This can be attributed to the high nutritional value of poultry meat, the absence of religious restrictions in most cultures, and the efficiency of industrial farming methods. The rapid development of this sector highlights the need for modern technologies at all stages of production – from transportation and slaughter to post-slaughter processing and traceability of the final product. This also presents significant opportunities for exporting halal meat from Ukraine, which has substantial potential for livestock development and the establishment of certified halal production facilities. The growing global demand for halal products can be met by leveraging Ukraine's competitive advantages, including high-quality meat and affordable pricing (Lupenko *et al*., 2022; Kryvenko, 2022).

The slaughter of poultry in compliance with halal requirements involves a series of technological operations, each subject to strict monitoring. Failure to meet any of these requirements may lead to the loss of halal status and reduce the product's quality and competitiveness. For instance, M. Ramli *et al*. (2024a) identified seven critical halal risk points (HRPs) in poultry slaughtering processes, covering transportation, hanging, stunning, slaughtering, bleeding, evisceration, and chilling. Each of these points requires careful monitoring to prevent violations of halal norms and ensure food safety standards. Particular attention is paid to electrical stunning, proper slaughtering techniques, effective bleeding, and sanitary conditions during evisceration and chilling. The growing global demand for halal products drives the expansion of production capacities and the adoption of advanced quality control methods. In this context, integrating traceability systems, automation, and modern technologies, such as RFID tags and blockchain, plays a crucial role in maintaining transparency and enhancing consumer confidence (Tieman & Williams, 2019; Ng *et al*., 2021). Thus, the increasing focus on halal standards necessitates strict adherence to technological and religious norms during poultry meat production. This requires a comprehensive approach that includes monitoring all stages of the technological process, implementing innovative technologies, and ensuring compliance with international standards for product quality and safety (Mylostyvyi, 2023).

The aim of this review was to critically analyse the control points of halal poultry slaughter, focusing on identifying problem areas, evaluating their impact on product quality and production efficiency, and examining modern approaches to optimising processes in accordance with Islamic standards. The review also addressed transparency and traceability within the production cycle. This review employed a systematic approach to analyse the technological processes involved in halal poultry slaughter. The methodology involved a comprehensive search and critical examination of relevant scientific literature, including peer-reviewed journal articles, conference proceedings, and industry reports. Additionally, international halal certification standards were consulted to understand the regulatory framework and compliance requirements. Risk management practices and quality control guidelines in food production were also reviewed. The analysis focused on identifying critical control points, assessing potential risks at each stage of poultry slaughter, and evaluating the impact of these risks on product quality and halal compliance. Modern technologies and traceability systems were also examined in the context of enhancing transparency and efficiency in halal poultry production. This multi-faceted approach allowed for a comprehensive understanding of the challenges and opportunities in halal poultry slaughter, leading to the development of informed recommendations for optimising

processes and ensuring compliance with both religious and technological standards.

Pre-slaughter factors and their role in determining poultry meat quality

Pre-slaughter factors, including catching, transportation, feed withdrawal, lighting, and handling, play a critical role in determining poultry meat quality. Stress or improper handling during these stages can lead to significant economic losses, either through carcass rejection or reduced quality (Petracci *et al*., 2010). These factors are generally classified into long-term and short-term influences. Long-term factors, such as feeding practices, genetic characteristics, housing conditions, and health status, affect poultry throughout their lifecycle. Short-term factors, including catching, transportation, shackling, stunning, and slaughter, exert the greatest impact within 24 hours prior to processing. These factors can significantly alter the physical and chemical properties of meat. The selection of poultry for slaughter requires careful management to ensure optimal muscle development, health, and growth at the time of processing. Genetic traits influence growth rates and carcass characteristics, making proper rearing practices essential. Feed withdrawal, typically lasting 8-12 hours, is necessary to empty the gastrointestinal tract and reduce the risk of faecal contamination during processing. However, an imbalance in withdrawal time can affect meat quality and yield. Short withdrawal periods may leave partially filled intestines, leading to contamination risks, while extended periods can cause excessive weight loss, metabolic changes, and increased pH levels in muscles, negatively impacting texture and shelf life.

According to A. Abdallah *et al*. (2021), halal processing standards impose strict requirements for pre-slaughter practices, including veterinary inspections and isolation from prohibited sources, such as pig farms or by-products. Some standards, like HAS 23103:2012 (2012) and MS 1500:2019 (2019), mandate facilities to be at least 5 km away from pig farms, which may pose challenges in areas lacking such infrastructure. Compliance also requires animals to be alive, healthy, and inspected by a veterinary officer prior to slaughter to meet halal criteria. Proper management during harvesting and transportation minimises stress and injuries, which preserves meat quality and prevents commercial losses. Feed withdrawal management is integral to maintaining hygiene and meat quality, as outlined by P. Kumar *et al*. (2022). Effective withdrawal facilitates gut evacuation, reducing contamination risks during processing. Poultry held off feed for excessive durations may experience glycogen depletion, resulting in elevated muscle pH and inferior meat texture. Extended fasting can also weaken the intestines, increasing the likelihood of rupture and contamination. Studies indicate that broilers lose 0.18-0.42% of their weight per hour after feed withdrawal, with males experiencing greater losses than females. After 16 hours, glycogen levels in breast and thigh muscles decrease by 0.27% and 0.22%, respectively, further compromising quality.

Environmental conditions, such as lighting and temperature, also influence feed withdrawal outcomes. Digestion slows in darkness, requiring at least four hours of light to stimulate gut activity. Adequate water availability mitigates dehydration, supports gut evacuation, and maintains carcass quality. In warm climates, shorter withdrawal periods are effective due to faster metabolic rates, while colder environments require longer periods to achieve similar results. Prolonged withdrawal may also lead to bile accumulation, increasing the risk of bile sac rupture and staining, which can affect flavour and visual appeal. M. Ramli *et al*. (2024b) emphasised the importance of integrating halal assurance systems (HAS, 2012) into production processes to manage risks related to feed contamination, medication use, biosecurity, and logistics. Implementing HACCP (1997) principles alongside halal compliance ensures

product safety and integrity. F. Mehak *et al*. (2024) highlighted the role of early biosecurity measures in preventing pathogen transmission, particularly among species that act as reservoirs for zoonotic diseases. Pre-slaughter preparation should include veterinary inspections and isolation protocols to mitigate infection risks. Managing feed withdrawal is a complex process that requires balancing gut evacuation efficiency with weight retention and meat quality. Short withdrawal periods increase contamination risks due to retained feed, while prolonged fasting weakens intestinal integrity, leading to ruptures. Extended periods also promote bile accumulation, risking staining and flavour alterations in carcasses. Optimal withdrawal strategies consider physiological and environmental factors to maintain product quality and halal compliance. Effective lighting, controlled temperature, and access to water further optimise gut evacuation and reduce processing issues, ensuring compliance with hygiene and safety standards.

Catching and loading: A critical pre-slaughter stage

The process of catching and loading poultry is a critical pre-slaughter stage that directly impacts meat quality and production efficiency. Improper handling, excessive stress, or injuries sustained during catching can lead to bruising, fractures, and dislocations, which reduce carcass quality and increase wastage (Saraiva *et al*., 2020). To minimise stress, catching is recommended during cooler periods, such as early morning or evening, when birds are calmer and less active. During manual catching, it is essential to follow established guidelines, including lifting poultry by both legs and avoiding carrying more than three poultry simultaneously. This approach reduces the risk of skeletal damage, muscle injuries, and dislocations. Additionally, dim lighting or low-intensity illumination can be used to calm poultry, facilitating handling and minimising stress-induced reactions. In larger poultry farms, mechanised systems, such as vacuum devices and conveyor belts, are increasingly employed to improve efficiency, reduce labour intensity, and enhance poultry welfare.

Mechanised methods provide several advantages, including reduced handling errors and lower injury rates. Vacuum systems, for example, enable rapid and uniform collection of poultry with minimal human intervention, while automated conveyors control movement and prevent overcrowding in transport containers. Modular transport systems, incorporating sliding drawers, further reduce injury risks and allow for the efficient loading of up to 6,000 poultry per hour with a team of three workers. Following the catching process, poultry are loaded into containers or modular systems equipped with sufficient ventilation and optimised stocking density to prevent overheating and overcrowding. Stocking density is adjusted based on environmental conditions; during hot weather, fewer poultry are placed in each container to facilitate airflow and cooling. Standard transport crates, which typically accommodate 12-14 poultry, are equipped with ventilation openings to maintain proper air circulation and prevent physical damage.

Transportation is another critical stage requiring meticulous planning to minimise stress and preserve meat quality. Transport time should be minimised, and temperature and ventilation within vehicles must be strictly controlled to prevent heat stress or chilling. Fluctuations in temperature, vibrations, sudden accelerations, and noise levels are additional stressors that can compromise poultry welfare and meat quality (Tkachuk *et al*., 2023). Forced ventilation systems and humidity control help maintain optimal conditions, reducing the risk of heat stress during warm weather or hypothermia in colder months. Studies by P. Govindaiah *et al*. (2023) emphasise that poor handling during catching and loading can cause measurable physiological stress

responses in poultry, such as elevated creatinine and total protein levels in the blood. These biochemical changes reflect physiological stress, which can negatively affect meat quality. Ensuring humane handling practices throughout catching, loading, and transport reduces stress indicators and helps maintain the quality of poultry products.

In halal production systems, additional requirements govern pre-slaughter handling. According to A. Abdallah *et al*. (2021), birds must undergo a health inspection before loading, and any weak or diseased individuals must be excluded to prevent compromising product quality. Furthermore, halal standards such as HAS 23103:2012 (2012) and MS 1500:2019 (2019) mandate strict controls to ensure animals are free from exposure to prohibited substances or contamination from non-halal sources. These guidelines also emphasise the importance of animal welfare at all stages, requiring that birds remain "alive or deemed alive" and are certified healthy by veterinary inspectors before slaughter. Effective management of catching, loading, and transport processes is essential to maintaining high product quality and ensuring compliance with halal standards. Mechanised systems and modular transport units play a crucial role in reducing injuries and stress while improving operational efficiency. Adherence to welfare protocols and pre-slaughter inspection requirements supports the production of high-quality halal poultry products, enhancing their competitiveness in global markets.

Unloading of poultry, ante-mortem inspection and preparation processes for poultry stunning

The unloading of birds at processing facilities represents a critical stage that requires meticulous handling to minimise stress and injury. Poultry are unloaded in designated areas near the primary processing unit, where containers are carefully removed from vehicles to reduce the risk of falls or impacts (Vieira *et al*., 2024). Holding units with poultry should be located indoors or under shelters to protect them from adverse weather conditions and to ensure adequate ventilation. It is essential to avoid abrupt or rough handling during unloading, as such practices can lead to increased stress, injuries, and reduced meat quality. Modern facilities often employ automated unloading systems, where modular containers are transferred via conveyor belts to the point of poultry extraction. These systems not only reduce the need for manual labour but also improve process efficiency and poultry welfare. The use of such systems ensures smoother and faster unloading, minimising stress and the likelihood of injuries. Moreover, ventilation and humidity levels within the unloading zone must be closely monitored to prevent excessive moisture accumulation, which could lead to respiratory complications or other health issues among birds. Workers are required to inspect the poultry during unloading, identifying any signs of injury or illness. Poultry that are unfit for processing due to injury or disease must be separated for further inspection, treatment, or humane disposal if necessary. Proper unloading practices, coupled with modern automation and continuous monitoring, play a key role in maintaining poultry welfare and optimising the efficiency of processing operations.

After poultry are removed from containers or modules, they must undergo thorough inspection to detect any injuries or damage sustained during transportation. Each batch is assessed to determine the physical condition of the poultry, including checks for head, leg, and wing injuries. This inspection is performed by a qualified veterinarian and must take place under adequate lighting to ensure effective visualisation. Following the ante-mortem inspection, poultry are prepared for slaughter by securing them in specialised fixtures designed to minimise stress and injury. Poultry typically calm down after an initial period of wing

flapping. Movement can be further reduced by gently restraining their legs or through brief physical contact with other parts of their bodies. The ante-mortem inspection procedure at the facility is strictly regulated to comply with international quality standards and religious requirements. The primary goal is to assess the overall health of the poultry, ensuring compliance with halal standards. The main aspects of this process are detailed in Table 1.

Table 1. *Ante-mortem inspection procedure*

Control points	Parameters
Comprehensive veterinary inspection	
Physical condition assessment	Detection of signs of diseases, injuries, abnormalities, or behavioural deviations. Poultry showing symptoms of infection or exhaustion are immediately culled.
External appearance evaluation	Particular attention is given to the skin, eyes, beak, and feathers to identify any pathological signs.
Sample testing	Selective testing for infectious agents or antibiotic residues, which is a mandatory requirement for exporting products to Muslim countries.
Compliance with halal requirements	
Selection of healthy poultry	According to Islamic standards, only healthy animals are eligible for slaughter. This is ensured through a comprehensive pre-selection process.
Supervision by a halal inspector	Each stage of the pre-slaughter inspection is carried out under the supervision of a certified representative of the Muslim community, ensuring compliance with Islamic rules.
Technological aspects of the process	
Infrastructure	Facilities certified for halal production must have designated areas for inspection to minimise contact between healthy and potentially diseased poultry.
Hygienic conditions	All operations are performed in sterile environments to prevent cross-contamination and maintain poultry welfare.

Source: developed by the authors

Ante-mortem inspection plays a crucial role in evaluating animal health and preventing the entry of contaminated carcasses into the food chain. According to P. Kumar *et al*. (2022), veterinary specialists assess the general condition of poultry to identify pathological conditions and exclude unfit animals. The inspection covers feather contamination, injuries, and signs of respiratory or gastrointestinal diseases, ensuring compliance with established standards. Once inspected, poultry are prepared for stunning, a process aimed at minimising suffering and ensuring effective exsanguination. Most facilities employ electrical water-bath stunning, although larger operations may use inert or mixed gas stunning systems. Maintaining optimal parameters for electric current or gas concentration is critical to achieving complete loss of consciousness without causing excessive trauma (Table 2).

Table 2. *Humane handling measures during ante-mortem inspection*

Control points	Parameters
Ethical handling	Poultry are kept in comfortable conditions that minimise stress and fear. Gentle handling is ensured.
Proper transportation	Poultry are delivered in containers preventing overcrowding and injuries, equipped with ventilation.
Access to water and feed	Water and feed are provided if waiting time exceeds regulated limits.
Waiting conditions	Poultry are kept in areas with controlled temperature and ventilation to prevent overheating or chilling.

Table 2. Continued

Control points	Parameters
Halal inspector supervision	Procedures are monitored by halal inspectors to ensure compliance with religious and welfare standards.
Ethical handling	Poultry are kept in comfortable conditions that minimise stress and fear. Gentle handling is ensured.

Source: developed by the authors

Humane handling during ante-mortem inspection forms an integral part of halal production standards. Emphasis is placed on reducing noise levels, using blue lighting, and maintaining comfortable climatic conditions to preserve product quality and meet international standards. These measures are essential for compliance with halal certification and improving animal welfare (Mehak *et al.*, 2024). Preparation for stunning must adhere to hygienic standards to prevent contamination with blood, which may contain residual pathogens, reducing the risk of zoonotic infections. As noted by P. Govindaiah *et al*. (2023), improper stunning methods may alter blood biochemistry, increasing creatinine, alanine aminotransferase, and triiodothyronine levels, which can negatively impact meat quality. Technological requirements for halal compliance are presented in Table 3.

Table 3. *Technological requirements for halal compliance*

Requirement	Characteristics
Dedicated slaughter zones	Separate areas are designated for halal processing to prevent cross-contamination with non-halal products.
Selection of healthy poultry	Only healthy birds, confirmed by inspection, are processed for slaughter.
Hygienic standards	All operations take place in sterile environments to prevent cross-contamination and meet halal standards.
Compliance with Islamic rituals	Religious requirements, including prayers and blessings, are observed throughout the process.

Source: developed by the authors

The transition from inspection to stunning must be swift to prevent poultry from regaining consciousness and to preserve welfare standards during slaughter (Table 4). Traditional halal slaughter without stunning is also practised, ensuring efficient blood drainage, reducing residual metabolites, and improving meat quality (Govindaiah *et al*., 2023).

Table 4. *Infrastructure and technological process control*

Control points	Parameters
Separate zones for slaughter and inspection	Facilities must have designated areas to maintain hygiene and meet halal requirements.
Sanitary conditions	All spaces and equipment must remain sterile to avoid contamination and comply with halal standards.
Handling practices	Systems must minimise stress and injuries. Ventilation, lighting, and temperature are optimised.
Modern equipment	Automated systems for slaughter and processing must meet halal standards and undergo regular inspections.
Process control	Documentation and monitoring systems ensure compliance with halal certification and production standards.

Source: developed by the authors

The integrated approach ensures compliance with halal requirements throughout the ante-mortem inspection and stunning preparation phases, securing animal welfare, product quality, and adherence to international trade standards.

Stunning of poultry: Techniques, parameters, and halal considerations

Stunning is a critical stage in poultry slaughter aimed at minimising stress and pain, improving bleeding efficiency, and facilitating subsequent processing operations. The most common method is electrical stunning in water baths, where current flows through the poultry body from the head to the legs. Achieving effective stunning requires precise calibration of voltage, current strength, and duration to ensure temporary loss of consciousness without violating halal production standards. According to international guidelines, stunning must be reversible and must not cause cardiac arrest or irreversible tissue damage. However, as noted by K. Al-Shammari (2021), inappropriate electrical stunning parameters may result in tissue damage, including muscle haemorrhages, bone fractures, and skin discolouration, which negatively impact carcass quality. These defects are often associated with high voltage or prolonged exposure to current, highlighting the importance of proper equipment calibration.

Different halal standards adopt varying approaches to stunning. In most cases, electrical stunning is permitted as long as it does not cause death before exsanguination. However, certain countries, such as Pakistan, prohibit any form of pre-slaughter stunning (Akbar *et al*., 2023). Meanwhile, I. Shahdan *et al*. (2016) proposed a system of six control points to ensure compliance with halal requirements, including monitoring stunning parameters to prevent violations of religious standards. Alternative methods, such as controlled atmosphere stunning using low-oxygen or inert gas mixtures (CO_2, nitrogen), are also gaining attention as means to reduce stress and physical damage. However, these methods require strict control of parameters and alignment with halal compliance regulations. Studies by M. Farouk *et al*. (2014) emphasise that the effectiveness of electrical stunning depends not only on technical parameters but also on the biological characteristics of the poultry, such as body mass, breed, and health status. Improper equipment settings can lead to insufficient or excessive stunning, impacting both animal welfare and meat quality.

I. Shahdan *et al*. (2017) highlight optimal stunning parameters, including a current of 105-150 mA and exposure durations of 4-6 seconds. These conditions enable effective immobilisation without causing severe tissue damage or compromising halal requirements. Nevertheless, K. Al-Shammari (2021) argues that traditional halal slaughter without stunning demonstrates advantages in reducing bacterial contamination and extending meat shelf life due to improved bleeding efficiency. At the same time, electrical stunning requires rigorous monitoring to ensure compliance with religious standards. Thus, adherence to the stunning parameters outlined in Table 5 is essential to integrate technological efficiency, humane treatment of poultry, and compliance with halal production requirements.

Table 5. *Electrical stunning parameters*

Control points	Parameters
Stunning process	Poultry are suspended upside down and passed through a water bath that conducts electric current. This process ensures rapid and effective immobilisation before slaughter.
Current intensity	The electric current must be strong enough (typically 105-150 mA) to induce loss of consciousness without excessive damage to the carcass (fractures, haemorrhages).

Table 5. Continued

Control points	Parameters
Hygiene conditions	The water in the bath must be clean, with added salt to improve conductivity, ensuring effective stunning.
Stress control	Poultry are hung in dimly lit areas or under blue lighting to minimise stress. Breast supports are used to reduce wing flapping.
Halal inspector supervision	A representative of the Muslim community ensures that stunning does not result in death prior to slaughter, maintaining halal compliance.

Source: developed by the authors

Continuous monitoring and calibration of stunning equipment are critical for maintaining quality standards and ensuring humane handling of poultry. Proper oversight at each stage helps prevent violations of halal principles while preserving the high quality of the final product.

Detailed examination of the poultry slaughter procedure

Following stunning, poultry are transported via a conveyor system to the slaughter machine, where the jugular veins and carotid arteries are severed using circular cutting blades. This procedure effectively drains blood from the poultry, which is essential for preserving meat quality. Precision in the incision is critical, as a deep cut may damage the nervous system, causing complications during feather removal, while a shallow incision may lead to insufficient bleeding and discolouration of the skin.

According to the comprehensive standard PBD24:2007 implemented in Brunei, the poultry slaughter procedure mandates strict adherence to Islamic principles, including the prohibition of mechanical slaughter (Deuraseh & Brunei Darussalam, 2020). Instead, slaughter must be performed manually with the mandatory invocation of Allah's name before each incision. The trachea, oesophagus, and major blood vessels must be severed to ensure complete blood drainage and a rapid death. The standard emphasises that the slaughter process must be conducted with the appropriate intention (niyyah) and must not involve actions likely to cause prolonged pain or suffering to the animal (Riaz *et al.*, 2021). Strict control over slaughter techniques is maintained in facilities employing automated systems (Table 6). Each stage is overseen by a certified halal inspector. Blades are checked for sharpness before each shift, and modern blood-draining technologies are implemented to minimise contamination of carcasses, thereby preserving product quality and safety.

Table 6. *Poultry slaughter control*

Control points	Parameters
Slaughter technique	Poultry undergo severing of the jugular veins and carotid arteries while leaving the trachea and oesophagus intact to ensure maximum blood drainage. Performed manually or automatically.
Bleeding time	A minimal time lapse (up to 15 seconds) is ensured between stunning and severing of blood vessels to prevent recovery of consciousness. Bleeding lasts 90-150 seconds for complete blood removal.
Halal inspector's role	A representative of the Muslim community must be present to ensure compliance with all halal slaughter norms, including reciting a prayer before each slaughter (audio recordings permitted).

Table 6. Continued

Control points	Parameters
Slaughter equipment	Blades must be sharp to ensure a clean cut without excessive tissue damage. Automated systems are adjusted to handle poultry of different sizes.
Hygienic conditions	Slaughter areas must maintain sterility to prevent microbial contamination of carcasses. Spraying systems are used to remove blood residues and tissue fragments.

Source: developed by the authors

The poultry slaughter process involves rapid severing of the primary blood vessels in the neck (carotid arteries and jugular veins) to ensure effective bleeding (Raj, 2004). It is critical that this step occurs immediately after stunning, as even a short delay can compromise meat quality and increase the risk of poultry regaining consciousness. In industrial settings, either mechanical methods (circular blades) or manual techniques (operator with a knife) are employed. Ritual slaughter, such as halal or kosher, often relies on manual cutting accompanied by prayers, although large-scale processing plants may incorporate automated systems to improve efficiency.

As highlighted by M. Farouk *et al*. (2015), debates regarding slaughter methods – with or without stunning – persist in many countries. While stunning is often viewed as a means to reduce animal suffering, ensuring that birds remain alive in accordance with Sharia principles until the incision is made is equally critical. Facilities that process high volumes of poultry typically employ electrical water-bath stunning, where attention to parameters such as frequency, voltage, and current strength is essential to prevent haemorrhages, broken bones, and deviations from religious standards. The slaughter process is a pivotal stage in halal meat production, requiring rigorous compliance with both religious and technological standards. The halal food industry continues to expand due to growing demands for quality, hygiene, and Sharia compliance. Quality management systems are implemented to address every stage of production – from slaughter to transportation. According to I. Vanany *et al*. (2019), particular focus is given to critical control points, including raw material preparation, equipment calibration, documentation, hygiene protocols, and personnel training.

Poultry scalding procedures and quality considerations

Scalding poultry is a crucial stage in the preparation of carcasses for feather removal, achieved through brief immersion in hot water. This process induces protein denaturation in feather follicles and loosens follicular structures, facilitating feather plucking (Kumar *et al*., 2022). The temperature and duration of scalding depend on the poultry species, age, and subsequent processing requirements. In "soft" scalding (50-53°C), the epidermis is preserved, whereas "hard" scalding (59-61°C) removes the waxy outer layer, potentially compromising the carcass's visual appeal. For young broilers, a "medium" scalding scheme (54-58°C for 60-120 seconds) is commonly applied to prevent damage to delicate skin and minimise microbiological risks.

The scalding temperature and duration significantly influence meat quality. High-temperature scalding (59-61°C) facilitates feather removal but may damage the skin, leading to dehydration, colour alterations, or reduced marketability of the carcasses. Conversely, lower-temperature scalding preserves skin structure but requires stricter parameter control to ensure effective feather removal. P. Govindaiah *et al*. (2023) emphasise that electrical stunning prior to scalding may alter the meat's water-holding capacity and muscle fibre structure. However, traditional halal slaughter methods

maintain pH stability and reduce myofibrillar protein fragmentation, improving the product's texture. Hygienic considerations during scalding are critical to preventing cross-contamination. Water in scalding tanks must be clean, with a counterflow renewal system, and may include permitted disinfectants to control microbial loads. Regular monitoring of water temperature and chemical composition is mandatory to ensure compliance with sanitary standards. For process optimisation, single- or multi-stage scalding systems are employed, allowing gradual temperature reductions that better prepare carcasses for further processing (Table 7).

Table 7. *Scalding process*

Control points	Parameters
Water temperature	Water temperature for scalding should range between 54-61°C, depending on the poultry species. Higher temperatures may damage the skin, while lower temperatures may fail to remove feathers effectively.
Immersion time	Poultry should be immersed in water for 45-90 seconds to ensure effective feather removal. Shorter times are suitable for young birds, while longer durations are needed for waterfowl.
Hygiene requirements	Scalding water must be free from contaminants to avoid cross-contamination. Filtration systems and regular water renewal are mandatory.
Water quality monitoring	Water temperature and composition must be continuously monitored. Chemical agents are used to reduce microbial contamination in the water.
Types of scalding systems	Single- and multi-stage scalding systems exist. Multi-stage systems gradually lower water temperature, optimising the process for various poultry species.

Source: developed by the authors

Feather plucking (defeathering) follows scalding and involves the mechanical removal of feathers. Automatic machines equipped with rotating rubber fingers are used to remove feathers without damaging the skin. Plucking intensity is adjusted based on the species and age of the poultry to prevent mechanical damage. P. Govindaiah *et al*. (2023) highlight that proper machine settings minimise stress and maintain tissue integrity. Automated feather removal systems ensure high efficiency but require regular maintenance and adherence to hygiene standards. Machines are equipped with adjustable speed and pressure systems, enabling adaptation to different poultry types (Table 8).

Table 8. *Feather plucking requirements*

Control points	Parameters
Type of equipment	Mechanical machines with rotating rubber fingers are used, adapted to the poultry species and age. These systems ensure gentle feather removal without skin damage.
Adjustment of plucking intensity	Intensity is adjusted according to poultry type. Lower speeds are used for young birds, while higher speeds suit mature birds.
Skin damage	The distance between the bird and rubber fingers must be monitored to prevent skin tears or bone fractures. Close proximity may cause mechanical damage.
Hygiene requirements	High hygiene standards must be maintained during plucking to prevent cross-contamination. Equipment is regularly cleaned of feathers and other contaminants.
Technology and maintenance	Plucking machines must be well-calibrated to optimise performance and minimise poultry damage. Regular maintenance ensures safety and process efficiency.

Source: developed by the authors

Feather distribution varies across different parts of the poultry body, with denser coverage in the lower sections requiring more effort for removal than the upper sections. Machines are equipped with additional rubber fingers in denser areas to improve efficiency. Proper feather removal is essential for preserving meat quality, as mechanical plucking prevents skin damage. Plucking machines operate using a cyclomatic design, where rotating rubber fingers contact the birds and extract feathers. Proper adjustment of the finger-to-bird distance is critical, as excessive proximity may cause skin tears and fractures, while too much distance may result in incomplete feather removal. Following plucking, flaming is applied to eliminate residual feather filaments and down through exposure to a blue flame for 5-10 seconds. This process improves carcass appearance and prevents surface defects. However, excessive heat must be avoided to prevent skin burns, stress, or additional damage, which could compromise meat quality.

Poultry evisceration and cooling procedures

Evisceration is a critical stage in poultry processing that involves the separation of edible and inedible internal organs from carcasses. This process is typically performed using mechanised systems to ensure efficiency and hygiene (Blevins *et al.*, 2018). Initially, an incision is made along the abdominal wall, from the keel to the cloaca, followed by the removal of internal organs such as intestines, heart, liver, and spleen using specialised equipment. After organ removal, veterinary inspection is carried out to examine carcasses and viscera for any potential pathologies or defects.

Edible offal, such as the liver and heart, is separated from other organs and thoroughly rinsed with water. To prevent microbiological contamination, water spraying systems with disinfectants are used. Waste materials that fail to meet quality or religious standards are removed and disposed of in accordance with sanitary regulations and halal production guidelines. Evisceration processes play a vital role in maintaining high sanitary standards and preserving meat quality. The evisceration process at the facility is conducted under strict regulations to ensure religious compliance, technological efficiency, and sanitary cleanliness (Table 9). Supervision by a certified halal inspector guarantees compliance with each stage of the process, from incision to the handling of edible offal. Automated systems help prevent mechanical damage and maintain hygienic conditions throughout carcass processing.

Table 9. *Requirements for poultry evisceration process*

Control points	Parameters
Compliance with halal requirements	Evisceration must be carried out by a certified operator in accordance with Sharia rules. The presence of a halal inspector is mandatory.
Equipment type	Automated or semi-automated systems are used to prevent damage to carcass integrity and internal organs.
Removal of internal organs	Organs that do not meet Sharia requirements (e.g., gall bladder) must be removed separately and disposed of in compliance with regulations.
Hygiene control	Work areas and equipment must be regularly cleaned and disinfected to prevent cross-contamination. Water used for cleaning must comply with sanitary standards.
Product integrity	Damage to skin or internal organs must be avoided, as this may affect product quality.
Waste disposal	Waste must be disposed of according to sanitary norms and halal production rules. Separate collection of organic and inorganic residues is mandatory.

Source: developed by the authors

Evisceration is a crucial stage in poultry processing that involves the removal of edible and inedible internal organs using mechanised systems to ensure efficiency, hygiene, and compliance with halal standards. The process includes precise incision, removal of organs, veterinary inspection, and separation of edible offal, such as the liver and heart, which are thoroughly cleaned. Strict hygiene measures, including regular disinfection and the use of water spraying systems with disinfectants, are implemented to minimise contamination risks. Waste materials are sorted and disposed of according to sanitary and halal requirements. Supervision by certified halal inspectors ensures adherence to religious standards, while automated systems help preserve carcass integrity and product quality throughout processing.

The cooling of poultry carcasses after slaughter is a critical stage for preventing microbial growth and ensuring the safety and quality of meat (Kumar *et al*., 2022). In modern processing facilities, poultry carcasses are typically cooled to approximately 4°C or below within 1-2 hours after evisceration. This is achieved through either water immersion or air chilling methods. Water immersion cooling, widely used in many countries, involves passing carcasses through a series of sequential tanks filled with cold water, often supplemented with approved disinfectants. This approach ensures rapid temperature reduction and the removal of residual blood or tissue fragments. Conversely, air chilling takes place at temperatures ranging from 2-7°C and requires 1-3 hours, during which carcasses are conveyed through a chilled chamber with air circulation. While water immersion cooling effectively reduces microbial contamination, it may result in slight water absorption by the carcasses. In contrast, air chilling may lead to minor weight loss due to surface dehydration. Therefore, the selection of the cooling method depends on processing requirements, quality expectations, and regional regulatory standards.

Effective post-mortem inspection techniques for poultry carcasses

Following the completion of the main stages of slaughter and carcass processing, a thorough post-mortem inspection is conducted to ensure the meat meets safety and quality standards (Kumar *et al*., 2022). This process focuses on identifying any signs of pathology, defects, or residual organ materials that could affect the product's suitability for consumption. Veterinary inspector or qualified personnel examine the external appearance of the carcasses and internal organs (if removed, these are inspected alongside the carcasses), paying attention to signs of inflammation, pathological changes, or residual digestive contents. If localised lesions or defects are detected, the affected areas are removed, and the carcass is re-inspected to determine its suitability for consumption. In cases of systemic pathology or infectious diseases, the carcass may be completely excluded from further processing. This approach ensures high food safety standards and maintains consumer confidence in poultry processing facilities (Table 10). Post-mortem inspection also involves evaluating meat quality to detect potential abnormalities. As noted by P. Govindaiah *et al*. (2023), assessing meat colour parameters, such as redness, helps identify residual haemorrhages often associated with electrical stunning. Conversely, traditional slaughter methods (without pre-stunning) demonstrate better blood drainage, reducing bacterial contamination risks and improving colour stability during storage.

Table 10. *Requirements for post-mortem inspection*

Control points	Parameters
Inspector oversight	Inspection of carcasses under the supervision of a certified halal inspector to ensure compliance with Islamic principles.
Carcass examination	Detection of physical defects, signs of disease, damage, or residual organs that do not comply with religious standards.
Meat quality	Evaluation of colour, texture, and odour to determine freshness and compliance with standards.
Hygiene standards	Use of sterile tools, disinfection of equipment, and cleaning of work areas to prevent contamination.
Removal of non-compliant carcasses	Immediate removal of carcasses that do not meet halal requirements or exhibit defects to maintain cleanliness in production.
Documentation	Maintaining records of inspection results to ensure transparency and compliance with standards.

Source: developed by the authors

During the post-mortem inspection, carcasses are cleaned of potential faecal contamination using chlorinated water or other approved disinfectants in specialised washing stations. After this, carcasses are thoroughly washed using spray nozzles to remove residual materials and then cooled to the required temperature during the chilling process. Carcasses that pass inspection and meet established standards are stamped and sent for further processing. Non-compliant carcasses or defective parts are discarded in accordance with sanitary regulations and halal production rules. This inspection stage plays a crucial role in maintaining high product quality, adhering to religious and hygiene requirements, and minimising risks for consumers.

Enhancing halal product traceability for consumer confidence

Traceability is a vital component of food safety systems, enabling monitoring of product movement from farm to consumer. It allows for the timely identification and resolution of potential food safety risks, enhancing consumer trust and transparency in production processes (Sucipto *et al.*, 2021). Halal product certification relies on international standards such as MS 1500:2009 (Malaysia) and GSO 993:2015 (2015), which regulate production, storage, packaging, and transportation processes (Table 11). Modern technologies, including RFID tags and blockchain systems, have been integrated to ensure continuous monitoring and recording of all production stages.

Table 11. *Halal product certification and inspection*

Control points	Parameters
Certification of facilities	Production facilities must be certified according to halal standards. Certification is issued by official bodies ensuring compliance with Islamic principles.
Continuous inspector presence	Certified halal inspectors must be present at every stage, from pre-slaughter inspection to final packaging, ensuring compliance with Islamic norms.
Equipment and facility inspection	Equipment, facilities, and processes are evaluated for compliance with halal standards. Contact with prohibited substances is strictly forbidden.
Documentation and traceability	All operations must be recorded and documented. A full record of production processes ensures transparency and compliance.
Staff training	All employees involved in production undergo specialised training on halal standards, including Islamic requirements and hygiene protocols.

Source: developed by the authors

Modern technologies, such as blockchain and RFID tags, provide automated monitoring of compliance with halal standards at all stages of production and logistics (Tieman & Williams, 2019). These technologies optimise traceability processes, reduce certification costs, and enable rapid responses to potential safety threats. However, even the most advanced systems cannot entirely replace inspector oversight, which ensures adherence to religious norms and evaluates production processes. Innovative methods for detecting hidden ingredients include molecular and spectroscopic techniques, integrated with artificial intelligence for analysing complex food matrices (Ng *et al*., 2021). Such tools enhance fraud detection accuracy, identifying prohibited components such as traces of pork or excessive alcohol levels. Despite their effectiveness, the widespread adoption of these methods faces challenges related to standardisation, equipment costs, and the need for global harmonisation of testing approaches.

Technologies such as the Internet of Things (IoT) and wireless sensor networks (WSN) support real-time monitoring of storage and transportation conditions (Ng *et al*., 2021). These systems help maintain appropriate temperature and humidity levels, minimising contamination risks. Special attention is given to integrating traceability standards to ensure compliance with halal requirements at all stages, including slaughter, processing, and packaging (Abdullah *et al*., 2019). Traceability systems preserve evidence of compliance and record product origin, which is critical for quality control and fraud prevention. As emphasised by S. Azam *et al*. (2021), the implementation of Halal Compliance Rating (HCR) systems, based on auditing key components such as hygiene, risk management, and knowledge of halal standards, enhances production transparency. These systems improve process monitoring, ensuring regulatory compliance and access to international markets.

Laboratory methods, including PCR and spectroscopy (FTIR, NMR), combined with chemometrics and artificial intelligence, allow for the analysis of complex food products and identification of prohibited ingredients (Ng *et al*., 2021). Despite their high accuracy, these approaches require substantial investment in equipment and method standardisation, posing challenges for large-scale implementation. Monitoring cross-contamination at all stages of production and logistics is essential for preserving the halal status of products (Supian, 2018). Combining blockchain technologies with audits and laboratory testing guarantees compliance with standards and increases consumer confidence (van der Spiegel *et al*., 2012). Thus, traceability systems play a key role in ensuring product quality, safety, and halal compliance, integrating modern technologies to enhance transparency and efficiency across production processes.

Animal welfare and meat quality

Animal welfare is a critical factor in ensuring high meat quality. Stress caused by poor handling or unfavourable conditions during transportation and slaughter can significantly degrade the flavour and texture of meat. Therefore, strict standards for animal handling are followed at processing facilities, including proper transportation, slaughter conditions, and pre-slaughter inspections. A key requirement is the use of stunning methods that minimise stress in poultry during slaughter. Animal welfare directly influences the quality of meat produced, as excessive stress during transportation and slaughter leads to deteriorations in physicochemical properties and an increased likelihood of defects (Kumar e*t al*., 2022; Sejian *et al*., 2024). Stress indicators such as respiratory rate, heart rate, and corticosteroid levels increase under poor handling or unsuitable housing conditions, contributing to quality issues – such as meat with excessive residual blood, bruises, or elevated microbial

contamination. Gentle handling, optimal stocking density in cages, and adequate resting periods before slaughter are essential factors for reducing stress levels and improving the commercial properties of poultry products.

Rising consumer awareness regarding halal standards has highlighted the importance of animal rearing methods, housing conditions, feeding practices, and slaughter techniques. Research by I. Aslan & H. Aslan (2016) emphasises the importance of certification and adherence to Islamic principles, which mandate humane treatment of animals during transportation and slaughter. Criteria such as the absence of contamination with haram ingredients and clear product labelling are crucial for maintaining trust among Muslim consumers. Ensuring animal welfare involves minimising stress and adopting humane slaughter practices, which, according to F. Mehak *et al*. (2024), also positively affect meat quality. Stress can trigger the release of toxic substances and the accumulation of metabolites in tissues, reducing product quality and increasing contamination risks. Halal slaughter methods promote more effective blood drainage, lowering the likelihood of residual pathogens and enhancing the organoleptic properties of meat (Govindaiah *et al.*, 2023). Most countries have enacted laws prohibiting animal cruelty and mandating humane slaughter methods, such as electrical stunning. Poor treatment of animals during slaughter affects not only their welfare but also the quality of the meat, including elevated levels of stress hormones, which impair texture and flavour characteristics.

Conclusions

The production of halal poultry meat requires strict adherence to both religious and technological standards. Effective control of the technological process, including ante-mortem inspection, stunning, bleeding, evisceration, chilling, and post-mortem inspection, is crucial for ensuring product quality and compliance with halal requirements. The identification of critical risk points enhances process control and prevents violations of standards. Studies highlight the need for implementing audit systems and risk analysis to optimise production processes and ensure food safety. This review has provided a comprehensive overview of the critical control points in halal poultry slaughter, highlighting the interconnectedness of technological processes, religious requirements, and animal welfare. By examining each stage, from pre-slaughter handling to post-mortem inspection and traceability, the study identifies potential risks and proposes strategies for optimising production processes. The practical value of this research lies in its potential to inform producers, processors, and regulatory bodies in their efforts to improve efficiency, ensure compliance with halal standards, and enhance consumer trust. The identified best practices and technological advancements can be implemented to minimise risks, improve product quality, and strengthen the competitiveness of halal poultry products in the global market. Furthermore, this review serves as a foundation for future research aimed at developing innovative solutions for halal poultry production, ultimately contributing to a more sustainable and ethical food industry.

Particular emphasis is placed on animal welfare, as stress during transportation and slaughter significantly affects the physicochemical properties of meat. Humane slaughter methods, such as electrical stunning, help reduce stress and improve organoleptic characteristics. The integration of modern technologies, including RFID tags, blockchain, and IoT systems, improves traceability and operational efficiency, ensuring compliance with halal standards and reinforcing consumer trust in the products. Further research should focus on improving slaughter control technologies, integrating automated quality assurance systems,

and optimising certification processes to meet the demands of international markets.

Acknowledgements

The authors would like to express their gratitude to Andrii Kramarenko, the official veterinarian of the Limited Liability Company "Dniprovskiy Poultry Complex" for providing valuable consultancy support during the preparation of this literature review.

Funding

None.

Conflict of Interest

None.

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Технологія халяльного забою птиці: критичний огляд контрольних точок

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Анотація. Халяльне виробництво має значний потенціал для подальшого розвитку, зумовлений зростаючим глобальним попитом на якісні, безпечні та етично виготовлені харчові продукти. Окрім задоволення потреб мусульманських споживачів, сертифіковані халяльні продукти стають дедалі привабливішими для ширшої аудиторії, яка цінує дотримання високих стандартів гігієни, простежуваності та якості. Сучасні тенденції підкреслюють важливість дотримання суворих вимог, що підвищує конкурентоспроможність халяльного виробництва на міжнародних ринках. У цьому літературному огляді розглядався технологічний процес забою птиці з акцентом на дотримання халяльних норм і вимог. Метою дослідження було виявлення ризиків на кожному етапі виробництва, оцінка їх впливу на якість продукції та визначення шляхів оптимізації виробничих процесів відповідно до ісламських стандартів. Аналіз базувався на огляді сучасної наукової літератури, стандартів сертифікації та практик управління ризиками в харчовому виробництві. Основні ризики пов'язані з такими етапами, як передзабійний огляд, оглушення, забій, знекровлення, потрошіння, охолодження та післязабійний контроль. Встановлено, що порушення на цих етапах може

призвести до механічних пошкоджень тушок, недостатнього знекровлення, мікробного забруднення або невідповідності релігійним вимогам. Впровадження систем управління ризиками, таких як HACCP, а також використання сучасних технологій простежуваності, включаючи RFID-мітки та блокчейн, може покращити прозорість, ефективність виробництва та відповідність міжнародним стандартам. Цінність дослідження полягає у визначенні напрямків удосконалення систем контролю технологічного процесу, зокрема шляхом інтеграції автоматизованих рішень для моніторингу критичних точок та аналізу якості продукції. Отримані результати можуть бути корисними для підвищення обізнаності щодо вимог до якості забою птиці в контексті сертифікації халяльного виробництва. Перспективи подальших досліджень включають вдосконалення технологій забою, розробку автоматизованих систем контролю та оптимізацію методів оцінки якості для підвищення ефективності виробництва та відповідності високим гігієнічним і релігійним нормам

Ключові слова: халяльне виробництво; безпечність і якість м'яса; критичні точки; управління ризиками; простежуваність

ANIMAL SCIENCE AND FOOD TECHNOLOGY

Journal homepage: https://animalscience.com.ua/en
Animal Science and Food Technology, 16(2), 77-95
Received 28.12.2024 Revised 22.04.2025 Accepted 22.05.2025

UDC 639.37:639.2.03
DOI: 10.31548/animal.2.2025.77

Quality assessment of fish pastes of increased biological value

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Suggested Citation:
Bal, I., Lebskyi, S., Lebska, T., Bal-Prylypko, L., & Slobodianiuk, N. (2025). Quality assessment of fish pastes of increased biological value. *Animal Science and Food Technology*, 16(2), 77-95. doi: 10.31548/animal.2.2025.77.

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Abstract. Providing the population of Ukraine with fish products is of particular relevance since their consumption level does not meet the recommendations for healthy nutrition. One of the directions that can solve this problem is to expand the range of fish pastes, which are affordable for a wide range of people. The aim of the study was to improve the formulation of fish pastes based on the meat of catfish (*Clarias gariepinus* (Burchell, 1822)), trout (*Salmo trutta fario*), pink salmon milt (*Oncorhynchus gorbuscha*), and plant-based raw materials, as well as to evaluate the new formulations based on a set of organoleptic indicators, flavour profile spectrum, energy value, and physicochemical research methods: moisture content – by drying the sample to constant weight; fat content – by the Soxhlet method; protein content – by the Kjeldahl method; ash content – by incineration of the sample. As a result of the research, the feasibility of combining the meat of the catfish, pink salmon milt and plant raw materials in the recipe composition of fish pastes was experimentally confirmed. Three new recipes for fish pastes were developed based on pre-salted and chopped catfish meat, trout and pink salmon milt, sautéed plant raw materials (onions, carrots), sunflower oil and spices. Studies of organoleptic indicators and the profile of the flavour spectrum determined the highest consistency indicators in fish pastes with catfish meat and pink salmon milt compared to the control and other formulations (9.5 ± 0.1 versus 8.5 ± 0.08 points). Regarding chemical composition, the fish paste samples were characterised by a high moisture content: 50.24 ± 0.17 in the experimental formulations versus 61.62 ± 0.84 in the control, % respectively. The protein content was 14.65 ± 0.19 in the paste with pink salmon milt versus 13.05 ± 1.18% in the control. The lipid content in the new paste formulations ranged from 32.12 ± 0.16 to 34.13 ± 0.21 versus 22.38 ± 0.17%, which determined their high energy value: 347.11-365.77 versus 253.64 Kcal/100 g in the control. The results of the studies showed the feasibility of combining catfish meat with pink salmon milt and vegetable raw materials in the formulation of fish pastes, which will expand the range of high-quality and valuable fish products

Keywords: catfish meat; pink salmon milt; plant raw material; organoleptic evaluation; descriptors; flavour spectrum; chemical composition

Introduction

Improvement of existing technologies for processing fish raw materials to create high-quality and safe food products has gained particular importance recently. This is due to the high nutritional value of fish raw materials, which contain essential amino acids, fatty acids, vitamins, macro- and microelements, and physiologically active carbohydrates. Providing the population of Ukraine with high-quality food products that meet modern FAO/WHO recommendations on the content of essential factors is one of the important tasks of innovative technologies (FAO/WHO, 2024). In this direction, the creation of food forms from natural raw materials using many ingredients is given special attention, because it allows combining raw materials of different origins to create products with specified properties of the biological value of protein, lipids, mineral components, and vitamin composition. On the other hand, relatively new types of aquaculture facilities, both in Ukraine and in the world, require the development of new technologies for their processing (FAO, 2022). Thus, in Ukraine and many countries around the world, the cultivation of the African catfish *Clarias gariepinus* (Burchell, 1822) from the family Clariidae is widespread (Sharylo *et al.*, 2020; Zadorozhnii, 2023). According to I. Bal (2024), modern technologies for processing this type of fish, as well as many freshwater fish, are

associated with the production of culinary products, cold and hot smoking, raw smoked sausages in combination with other aquatic organisms, animal and plant raw materials, smoked sausages using liquid smoke. Since many innovative technologies are associated with the production of minced meat systems, considerable attention is paid to ensuring their specific structure and consistency. N. Bozhko *et al*. (2021) proved that combining freshwater silver carp meat with duck meat improves the strength and elasticity of the system, water-binding and water-retaining capacity, and contributes to improving the structural, mechanical and organoleptic properties of sausage products. N. Walayat *et al.* (2022) determined the effectiveness of using cryoprotectants in minced fish products to improve their gelling ability. The improvement of sensory and structural features of minced fish-based systems is facilitated by the use of potato starch, and hydrolysate from fish swim bladder (Ernawati *et al*., 2021). The Ukrainian market is dominated by freshwater aquatic organisms (UIFSA, 2024). The improvement of meat properties for the production of high-quality canned products is the focus of the study by S. Arokiyaraj *et al*. (2024), which involves treating the raw material with various acids to ensure the maturation of the canned products.

Despite a significant amount of scientific research in the field of fish product technology, the issue of improving existing fish paste technologies based on the principles of food combinatorics using meat of different fish species and plant raw materials remains relevant. The work aimed to improve the recipe composition of fish pastes based on meat of Clarias catfish, trout, pink salmon milt and plant raw materials and to research organoleptic indicators, flavour spectrum profile and energy value of new fish paste recipes. The objectives of the work were to study the compatibility of fish raw materials, namely meat of Clarias catfish, trout, pink salmon milt, plant raw materials, to form the recipe composition of fish pastes, to determine organoleptic indicators, flavour spectrum profile and energy value of new recipes. The scientific novelty of the work lies in the formation of a recipe composition of high-quality fish pastes based on a complex of organoleptic indicators, palatability and energy value based on domestic raw materials.

Literature Review

Fish pastes are a snack food product made by physically or chemically grinding, mashing, mincing, or pressing the meat of fish or invertebrates, and mixing the minced mixture with ingredients of plant or animal origin to achieve a homogeneous consistency. In this context, the use of aquaculture objects – clarias catfish and trout to improve the formulation of fish pastes is of particular importance (Okonkwo *et al*., 2020; Knaus *et al*., 2021). The technology of pasty products allows for combining raw materials of different origins and, based on the principles of food combinatorics, forming products with specified properties of organoleptic indicators, biological and energy value, and structural and mechanical features (Lebska *et al.*, 2021).

The technology of pasty products is based on obtaining a minced emulsion with specific structural and mechanical properties. In this regard, many studies have been devoted to the factors that affect gelling and emulsifying ability. Thus, H. Luo *et al.* (2020) showed the feasibility of adding potato starch at levels of 8 and 5%, which improves the gel strength and taste of surimi. However, adding starch to minced meat products from washed minced fish contributes to an increase in carbohydrates, which reduces their nutritional value by reducing the content of proteins and essential amino acids.

Research by M. Sapatinha *et al.* (2025) determined the effectiveness of adding protein hydrolysates obtained after enzymatic hydrolysis of substandard fish caviar on the structural and mechanical properties of minced products from silver carp meat and enriched with fish

oil. It was shown that hydrolysates contribute to the strengthening of the structure of fish sausages, improve sensory properties and slow down fat oxidation and microbial spoilage. The use of hydrolysates of substandard fish caviar is seasonal. On the other hand, fish caviar can be at different stages of maturation, which are not controlled during manufacturing these products. Therefore, the use of this method in industrial conditions is very problematic. On the other hand, it is a very good idea to add caviar hydrolysates as a source of complete proteins, lipids and vitamins (Adebisi & Oshibanjo, 2019).

Fish pastes and other minced fish food products are subject to rapid spoilage. Non-thermal disinfection, such as cold plasma (CP), can be used to prevent the growth of microorganisms (Andoni *et al*., 2021). Using the example of chicken sausages, the effect of ultraviolet (UV) irradiation (for 200 and 400s) and CP (power 30 and 70 W for 200 and 400s) was investigated. CP had a greater effect on the appearance of sausages, effectively inhibiting the development of microorganisms and a longer shelf life. Non-thermal disinfection of sausages has significant advantages, because it does not cause lipid oxidation and denaturing changes in the protein component (Filho *et al*., 2021). Unfortunately, there is no industrial equipment for processing food products using CP, and the issues of digestibility of food products after this processing have not been studied.

Effective use of by-products from fish raw material processing opens up opportunities for new industries in the case of their deep processing. A. Ampitiya *et al.* (2023) showed the feasibility of extracting collagen from the skins of fish species such as yellowfin tuna (*Thunnus albacares*), seer fish (*Scomberomorus commerson)* and Asian sea bass (*Lates calcarifer*). The results of the studies indicate the possibility of using the extracted collagen as a structure-forming agent, including in minced fish products. The problem of unifying the quality of collagen extracted from the skin of different fish species and specific recommendations for its use in minced fish products remains.

A positive effect of the hydrolysate of the swim bladder gelatin (SBGH) of the fish *Labeo rohita* on the texture, sensory, microbial properties, and fat oxidation processes in cooked sausages enriched with polyunsaturated fatty acids has been determined (Cruz-López *et al.*, 2023). Adding 3% SBGH to minced sausage systems showed higher hardness, cohesion, stickiness, slowing down of fat oxidation processes and safety throughout the entire storage period at 4°C for 30 days compared to control samples. Based on these research results, it is recommended to add hydrolysates of swim bladder gelatin to minced fish in the manufacture of sausage products, which will help slow down oil oxidation and microbial spoilage and improve the structural and mechanical properties of sausages. The disadvantage of this work is the difficulty in preparing this raw material and its small amount to manufacture gelatin hydrolysates. The swim bladder is present only in bony freshwater fish, the total catch of which in Ukraine is significantly less than that of marine ones (Public report..., 2024).

The search for ways to optimise the recipe composition of minced meat products provides grounds for improving both the product's nutritional value and its structural and mechanical properties. Scientists N. Aukkanit *et al.* (2020) established the effects of different levels of *Hylocereus dragon fruit peel powder undulate* (DFPP) on the physical, chemical and sensory properties of emulsion sausages. In emulsion sausage samples, pork fat was replaced with 0.5, 1.0, 1.5, 2.0, and 2.5% DFPP. The sausage's moisture, ash, and crude fibre contents increased with increasing amounts of this additive. High-content DFPP increased sausage firmness, elasticity, stickiness and chewiness but reduced cohesion. The addition of 2.0% DFPP was recommended, which did not significantly affect the sensory evaluation of

appearance, taste, texture and overall acceptability. Based on the conclusions of the authors of this work, doubts arise about the feasibility of using DFPP instead of lard, because there is no comparative analysis of nutritional value. The feasibility of using pectin from apple peels using microwaves has been proven in model sausage systems (Aldemir *et al.*, 2024). It was determined that pectin emulsions show higher stability at a pectin mass fraction of 1.0%. Therefore, apple peel pectin can potentially be used for fat reduction in minced meat systems for sausage production.

Researchers S. You *et al.* (2022) established the effect of improving the nutritional value and sensory properties of fish sausages by adding 15% textured soy protein (TSP), 8% potato starch and 5% lard. During 180 days of storage, the moisture retention capacity, colour, and gel strength decreased, but weight losses during cooking and thawing were lower than the control. However, the processes of secondary lipid oxidation and the accumulation of protein degradation products were more pronounced. However, the basic nitrogen value was higher. Thus, these data allowed the authors to recommend the use of soy protein in fish sausages in order to improve the gel strength and sensory properties of fish sausages.

The use of various additives to improve the emulsification ability of minced meat products contributes to the improvement of technologies and the quality of the final product (Pelykh *et al.*, 2020). The addition of regular and defatted fenugreek seed powder *Trigonella Foenum-Graecum* (TFg and DTfg, respectively) at 2.0% and 4.0% to meat emulsions determined their impact on improving the quality of emulsion-type meat products with vegetable oils as substitutes for animal fat (Patriani *et al.*, 2023). Cooking losses and fat and liquid separation were lower in TFg, and Dtfg samples combined with starch. Lipid oxidation was higher in samples with TFg than with Dtfg or starch. Hardness, chewiness and stickiness were lower in TFg and Dtfg samples than in starch samples. These results show that TFg powder is a promising raw material for improving the quality of emulsion-type meat products with vegetable oils as animal fat substitutes. The disadvantage of these studies is the lack of data on the change in the biological value of the final product when using these additives.

Thus, E. Alagöz & C. Sarıçoban (2024) studied the effects of roasted and unroasted turpentine (*Pistacia terebinthus*) on the colour, emulsion capacity, fluidity, emulsion stability, microstructure and textural properties of meat emulsions. Meat emulsions were created by adding roasted and unroasted turpentine to beef in amounts of 0.0, 0.1, 0.3, and 0.5%. Emulsion capacity and stability increased with the addition of turpentine, with the highest value of emulsion capacity (233.50 ml oil/g protein) and stability (74.50%) observed at a turpentine concentration of 0.3%. The use of roasted turpentine contributed to an increase in emulsion stability and sample capacity compared to unroasted. Thus, it is recommended to add turpentine to emulsion-type products with a high-fat content, which will contribute to improving technological and functional properties. The authors of this study did not consider the hypothetical mechanisms of the influence of turpentine additives on the emulsion properties of minced meat products.

Researchers N. Bozhko *et al.* (2021) proved the feasibility of combining the meat of freshwater silver carp (*Hypophthalmichthys molitrix*) with duck meat (*Anas platyrhynchos*) in the composition of semi-smoked sausages. The optimal recipe with the highest quality indicators of semi-smoked sausages from duck meat and freshwater aquaculture fish at a ratio of 50:30 was determined, which provides improved strength and elasticity of the system, water-binding and water-retaining capacity, sensory evaluation indicators, and an ideal protein: fat ratio (1:1). It would be desirable to assess the nutritional value of the final product.

The original design of the fish paste recipe was created by A. Menchynska *et al.* (2021). Based on theoretical studies, using carp meat with caviar of freshwater carp and sea fish - capelin and sunflower oil is justified. It is shown that due to the high content of phospholipids in fish caviar and sunflower oil, which are natural emulsifiers, the elasticity of the minced meat system is ensured, the organoleptic properties and the spectrum of the palatability profile are improved. Also, due to the content of biologically valuable essential amino acids, and fatty acids of the omega three family in this raw material, these fish paste recipes belong to health food products.

The effectiveness of combining fish raw materials of different origins in the minced meat system has been shown in the studies of A. Menchynska *et al.* (2021). The feasibility of using catfish meat as a raw material for the production of fish sausages has been theoretically substantiated and experimentally confirmed. The authors have developed a recipe composition of minced meat systems for the production of raw smoked fish systems based on catfish meat with the addition of mackerel, scallops and lard. Combining raw materials of different origins contributes to an increase in nutritional value. However, the developed recipes for fish sausages belong to the "elite" food products and are not available to a wide range of the population.

The preliminary preparation of raw materials before manufacturing finished products significantly affects the quality of the finished product. In this regard, research by S. Kunnath *et al.* (2022), determined the effect of high pressure on modifying the structure and functional properties of minced products from pink perch meat (*Nemipterus japonicus*). Fish mince significantly changed in viscosity when processed at 200, 400, and 600 MPa. In contrast to thermal gels, pressure-induced gels were smooth, white, and elastic. Reduction of reactive SH groups, which participate in forming gels and emulsions, occurred in samples treated at 400 and 600 MPa due to the formation of disulfide bonds. The use of pressure contributed to the reduction of microbial contamination by 2-3 logarithmic cycles. It is recommended to treat minced meat with a pressure of 200 MPa, which does not significantly affect the quality of the structure and functional properties of the protein. Unfortunately, the authors did not study changes in the biological value of the product after this treatment.

L. Chen *et al.* (2024) proposed a combined processing of fish raw materials that contributes to the preservation of its sensory properties. The effect of different temperatures (18, 20 and 50°C) on raw pieces of grass carp (*Ctenopharyngodon idella*) under pressure of 300, 400 and 500 MPa. Increasing pressure caused shrinkage of fibres and compaction of the structure, but the content of myofibrillar proteins decreased with increasing temperature. The results of these studies will help control the quality of fish and will contribute to the development of appropriate means to improve the quality of both raw materials and food products from fish.

Thus, modern technologies of minced products, as the basis for the manufacture of sausage and pasty food products, are associated with the improvement of their recipe composition by using ingredients that are not traditional for these products, as well as with the use of structure-forming agents to ensure the emulsion and gel structure typical for these products. However, many issues regarding the expansion of the spectrum of use of new types of raw materials and a comprehensive assessment of the palatability and nutritional value of minced products remain unresolved. The purpose of these studies was to improve the recipe composition of fish pastes based on domestic raw materials – meat of catfish, trout and pink salmon milt, organoleptic evaluations, characteristics of the spectrum of the flavour profile and energy value of the products were carried out.

Materials and Methods

The research was conducted during 2023-2024 in the laboratory of the Department of Meat, Fish and Seafood Technology of the Faculty of Food Technology and Quality Control of Agricultural Products of the National University of Life and Environmental Sciences of Ukraine. The formulation of the fish pastes was based on an assessment of the compatibility of raw materials, namely – Clarias catfish meat from aquaculture in Ukraine, trout, pink salmon milt, vegetables (onions, carrots), sunflower oil, tomato paste and spices. The control recipe used was the one from the experiments by A. Menchynska *et al*. (2021). The fish was cut into fillets, salted with 5% salt for 24 hours at room temperature and ground on a cutter to a particle size of up to 1 mm. Pink salmon milt was thawed at room temperature for 4-6 hours, dry-salted with 5% salt for 12 hours at 4°C and ground to 1 mm. Onions and carrots were ground and sautéed in sunflower oil. The compatibility of raw materials was assessed based on combining fish meat and pink salmon milt in different ratios, the recipe composition of fish pastes was formed and the ingredients were dosed in a certain amount. Emulsification of the minced mixture was carried out by gradually adding sunflower oil in accordance with the amount specified in the recipe (Table 1).

Table 1. *Formulation of fish pastes*

Ingredients	Quantity of ingredients, %			
	control (Menchynska *et al*., 2021)	sample 1	sample 2	sample 3
Carp meat	70.0	-	-	-
Clarias catfish meat	-	30.0	45.0	30.0
Trout meat	-	30.0	15.0	15.0
Salted milt	-	-	-	20.0
Carrot	-	9.0	9.0	5.0
Sautéed onion	5.0	5.0	5.0	5.0
Tomato paste 30%	10.0	10.0	10.0	10.0
Sunflower oil	6.8	12.2	12.2	12.7
Table salt “Extra”	3.0	3.0	3.0	1.5
Sugar	0.5	0.5	0.5	0.5
Acetic acid 9%	0.2	0.2	0.2	0.2
Ground black pepper	0.05	0.05	0.05	0.05
Ground allspice	0.02	0.02	0.02	0.02
Ground coriander	0.03	0.03	0.03	0.03
Water	4.4	-	-	-
Total	100.0	100.0	100.0	100.0

Source: authors’ development

For the organoleptic analysis of fish pastes, a five-point scale was developed in accordance with the recommendations (Tkachenko *et al*., 2020). The assessment results were expressed in points on a conditional scale with an increasing sequence of numbers (Table 2). Organoleptic evaluation of fish caviar-based pastes was carried out according to the following indicators: appearance, colour, taste, smell, and consistency.

Table 2. *Scoring scale for organoleptic evaluation of fish pastes*

Indicator	Indicator characteristics	Point
Appearance	Homogeneous, pasty mass without grains	5
	Homogeneous, pasty mass, slightly grainy	4
	Heterogeneous mass, moderate granular mass	3
	Heterogeneous mass, very granular mass	2
	Heterogeneous, highly granular mass with a large number of foreign impurities and lumps	1
Colour	White or light orange or light pink, uniform throughout the mass	5
	With a greyish tint, uniform throughout the mass	4
	With a greyish tint, slightly heterogeneous throughout the mass	3
	Grey with orange or pink flecks, non-uniform throughout the mass	2
	Dark grey, non-uniform throughout the mass, with dark inclusions	1
Consistency	Homogeneous, pasty without grains	5
	Homogeneous, pasty with single grains	4
	Heterogeneous, moderate grainy	3
	Heterogeneous mass, very granular	2
	Heterogeneous, lumpy	1
Taste	Harmonious, typical of this type of product, with a caviar flavour, the taste of freshwater fish is not felt	5
	Harmonious, typical of this type of product, the taste of freshwater fish is barely noticeable	4
	Harmonious, typical of this type of product, the taste of freshwater fish is moderately pronounced	3
	Fishy, with a hint of vegetable components, no milty taste	2
	Strongly pronounced fishy flavour, the taste of other components is almost not felt	1
Scent	Pleasant, typical of this type of product with a milty aroma	5
	Slight fishy smell	4
	Fishy smell moderately pronounced	3
	The fishy smell is strongly pronounced	2
	The fishy smell is very strongly pronounced	1

Source: authors' development

When assessing the consistency of fish pastes, tenderness, homogeneity, and uniformity were determined. To determine the smell, typicality, intensity, and the presence of specific and other foreign odours were determined. The total chemical composition of fish pastes was determined by moisture, protein, fat and ash content. The mass fraction of protein was determined by the total nitrogen content by the Kjeldahl method by the requirements of DSTU 8030:2015 (2017). Mineralisation of samples was carried out in a digester Velp Scientifica series DK6 (Italy) with a vacuum pump (JP). The distillation process was carried out on the apparatus Velp Scientifica UDK 129. The mass fraction of lipids wasdetermined using the Soxhlet extraction-weight method on the Soxhlet SOX 406 Fat Analyzer, according to DSTU 8717:2017 (2019). Mass fraction of ash-by weight method after mineralisation of the sample in a muffle furnace at a temperature of 500-600°C according to DSTU 8718:2017 (2019). Mass fraction of moisture – by drying the samples to constant mass at 100-105°C (DSTU 8029:2015, 2017). The caloric content of fish pastes was determined using a calculation method.

The taste of fish pastes was evaluated using flavour spectrum profilographs in accordance with the descriptors developed by the authors according to DSTU ISO 6564:2005 (2006). To substantiate the feasibility of combining

freshwater fish meat with pink salmon milt and raw materials of plant origin, an organoleptic assessment of the compatibility of these ingredients in fish pastes was carried out. Experimental studies were carried out in 3 replicates, the reliability of differences was assessed using the Student's t-test at $P \leq 0.05$.

Results

Organoleptic assessment of the quality of a food product forms the first impression of the consumer. The results of studies of the comparative characteristics of experimental samples of fish pastes of different formulations (1, 2, 3) in comparison with the control (C) are given in Table 3.

Table 3. *Comparative evaluation of organoleptic indicators of fish pastes of different formulations, in points*

Samples	Indicator characteristics and its points					
	Appearance	Aroma and taste	Consistency	Structure	Colour	Overall rating
C	Typical fish paste (4.3±0.7)	Typical for this type of product (3.6 ± 0.5)	Pasty, smearing (4.0 ± 0.3)	Homogeneous, with inclusion of muscle fibres (4.0 ± 0.1)	Light grey with a pink tint (4.2 ± 0.1)	20.1 ± 0.4
1	Typical fish paste (4.5 ± 0.2)	Typical for this type of product (3.9 ± 0.2)	Pasty, smearing (4.3 ± 0.4)	Homogeneous, with inclusion of muscle fibres (4.0 ± 0.2)	Light pink uniform throughout the mass (4.5 ± 0.1)	21.2 ± 0.5
2	Typical fish paste (4.7 ± 0.4)	Typical for this type of product (4.2 ± 0.1)	Pasty, smearing (4.3 ± 0.5)	Homogeneous, with inclusion of muscle fibres (4.0 ± 0.1)	Light pink uniform throughout the mass (4.7 ± 0.4)	21.9 ± 0.3
3	Typical fish paste (4.9 ± 0.2)	Typical for this type of product (4.5 ± 0.1)	Pasty, smearing (4.9 ± 0.3)	Homogeneous without inclusions (4.9 ± 0.1)	Light pink, uniform throughout the mass (4.9 ± 0.1)	24.1 ± 0.1

Source: authors' development

In appearance, all fish paste samples met the requirements for this product. The aroma and taste were also characteristic of fish pastes due to the fact that they included crushed salted fish raw materials: in the control sample from carp, in 1 and 2 – catfish and trout meat, in 3 – catfish, trout meat and pink salmon milt. A comparative analysis of the organoleptic indicators of fish pastes of different recipes shows that the overall score was better for fish paste based on catfish, trout and pink salmon milt 24.1 versus 20.1 in the control sample and 21.2 and 21.9 in recipes with a combination of catfish and trout meat, respectively. The control sample and samples No. 1 and No. 2 were characterised by a homogeneous consistency but with the inclusion of muscle tissue. A comparative characteristic of the chemical composition of fish pastes of different formulations is shown in Figure 1.

The moisture content in the control sample of fish paste was 61.62 ± 0.84%, which is 11% higher than that in the experimental ones. The amount of protein in the control sample was 13.05 ± 0.18%, which is less than in the experimental ones by an average of 1%, the number of mineral compounds ranged from 1.34 to a certain lesser amount in sample No. 3. The level of lipids was from 22.38 ± 0.17 to 34.13 ± 0.21 and in the experimental samples it was 10% higher than in the control, which ensured their high energy value (Fig. 2).

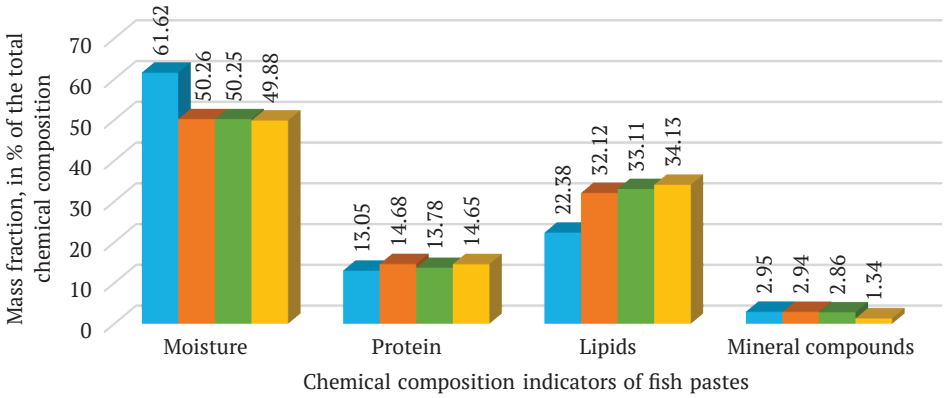

Figure 1. Comparative characteristics of the chemical composition of fish pastes of different formulations

Source: authors' development

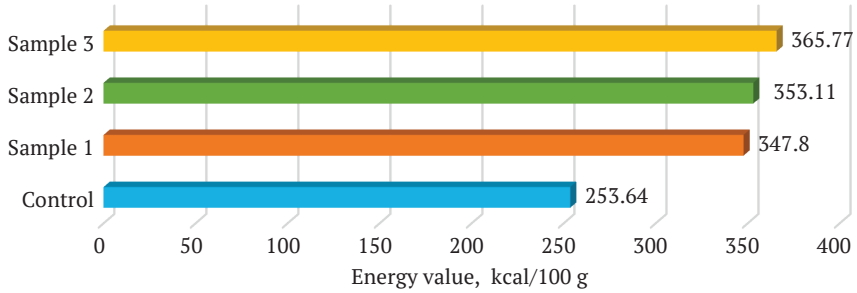

Figure 2. Estimation of the energy value of fish pastes of different formulations, kcal/100 g

Source: authors' development

Analysis of the results showed that sample No. 3 had the highest energy value, which is 365.77 kcal versus 253.64 kcal in the control and 353.11 kcal in sample No. 2 and 347.8 kcal in sample No. 1. To assess the palatability of fish pastes, the flavour spectrum profile method was used, which is one of the group of methods for describing sensory characteristics and is considered fundamental for many other descriptive methods. The concept of flavour is understood as the combined effect of taste properties, aromatic perception and tactile sensation in the oral cavity (DSTU ISO 6564:2005, 2006).

The flavour spectrum profile method is an attempt to characterise "flavour", taking into account all the descriptors that form the overall impression of the product. The use of this method allows for describing the overall impression of the product based on five main criteria: the nature of the descriptors, their intensity, the order in which these descriptors appear, aftertaste, and their completeness (a phenomenon expressed by the overall impression of the compatibility of the product's components). During the study, descriptors of the organoleptic profile were developed and the "ideal" organoleptic spectrum of the profile (standard) was determined. To build the "ideal" organoleptic spectrum of the profile, a consumer tasting was conducted to obtain data on the level of desirability of the intensity of the descriptors according to five samples of their intensity scale. The results of the profile analysis of the palatability of fish pastes are given in Table 4.

Table 4. *Profile analysis of palatability of fish pastes*

Descriptors	Intensity of characteristics of different fish paste formulations, points				
	Standard	Control	1	2	3
Aroma and taste characteristics					
harmonious	5.0	4.5	4.0	5.0	5.0
fishy	5.0	3.0	4.0	4.0	4.5
typical	4.0	3.0	4.0	4.0	4.0
sweet	1.5	1.0	1.0	1.0	1.0
salty	2.8	2.5	2.5	2.5	2.8
with the aroma and taste of added vegetables	3.0	3.0	3.0	3.0	3.0
Characteristics of the structure					
pasty	5.0	4.0	4.0	4.0	5.0
homogeneous	3.5	3.0	3.0	3.0	3.0
heterogeneous with inclusions	1.5	1.0	1.0	1.0	-
Consistency					
tender, juicy	3.5	2.5	2.0	3.5	3.5
dry	1.5	2.5	2.0	1.5	1.0
General impression	5.0	3.5	3.0	3.5	5.0
Total points	41.3	33.5	33.5	36.0	37.8

Source: authors' development

Harmonious aroma and taste with an intensity of 5.0 points is characteristic of the standard and samples No. 2 and No. 3. A lower number of points was received by Sample No. 1 and the control sample: 4.0 and 4.5, respectively. The descriptors "fish aroma and taste" were more pronounced in recipe No. 3 – 4.5 points compared to the standard sample of 5.0 points and other samples – 4.0 in samples No. 1, 2 and in the control – 3.0 points. According to the descriptor "typical", all fish paste samples, except for the control sample, received the same number of points – 4.0. The control sample – 3.0 points. "Sweet taste" was the same for all experimental samples and was 1.0 points compared to 1.5 in the standard. The descriptor "salty" was characterised by the same number of points in the standard and sample No. 3 – 2.8 points. The other samples received 2.5 points. The number of points in all samples of fish pastes according to the descriptor "with the aroma and taste of added vegetables" had the same rating – 3.0 points.

According to the descriptors of the structure, the best "pasty" was determined in the fish paste sample No. 3 – 5 points, as in the standard. Other samples received a score of 4.0 points. The homogeneous structure of fish pastes was determined in all samples, but not better than the standard and was 3.0 points. The descriptors "heterogeneous with inclusions" were determined in all samples, except No. 3. The descriptor "tender, juicy consistency" received the highest number of points in the fish paste samples No. 2 and No. 3, – 3.5 points, that is, on a par with the standard. The dry consistency was expressed to a greater extent in sample No. 3. The descriptor "general impression" was the same between the standard and sample No. 3 and was 5.0 points. According to the "total points", the highest number of 37.8 points was received by sample No. 3 with pink salmon milt compared to the standard – 41.30 and 33.5 and 36.0 in other experimental formulations. For a more visual perception of the research results, detailed organoleptic spectra of the flavour profile of each sample were constructed and compared with the "reference" profile of fish paste (Fig. 3-6).

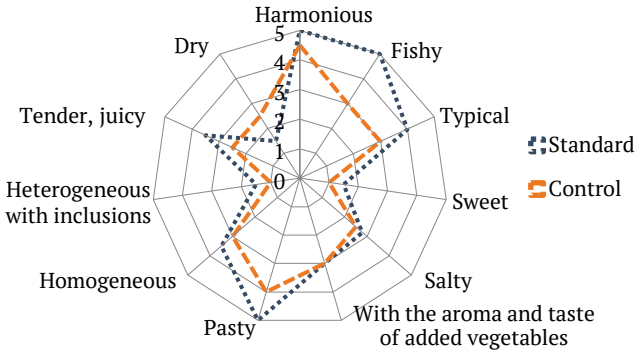

Figure 3. Profilogram of the flavour profile spectrum of the standard and control samples of fish pastes

Source: authors' development

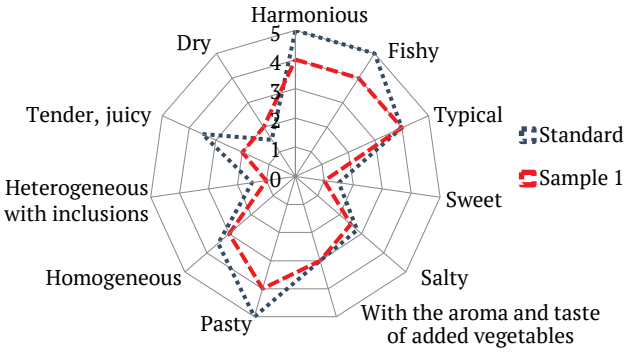

Figure 4. Profilogram of the flavour profile spectrum of the standard and sample fish paste according to recipe No. 1

Source: authors' development

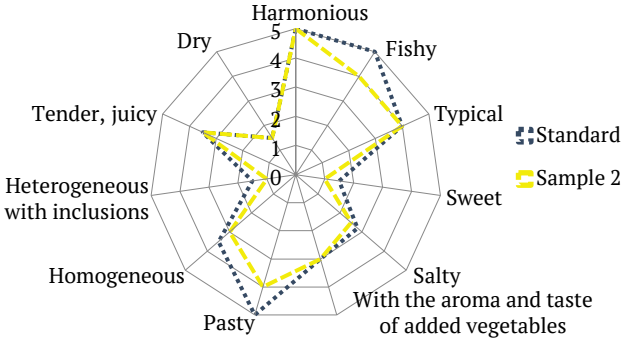

Figure 5. Profilogram of the flavour profile spectrum of the standard and sample fish paste according to recipe No. 2

Source: authors' development

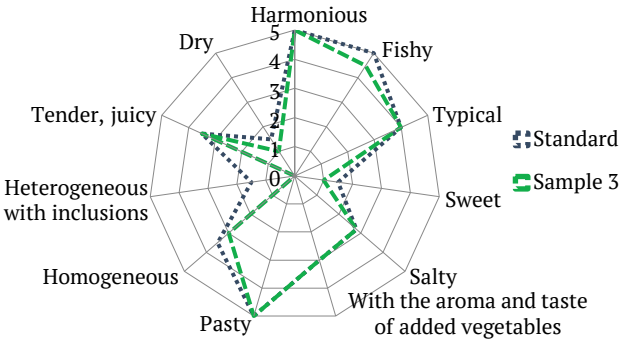

Figure 6. Profilogram of the flavour profile spectrum of the standard and sample fish paste according to recipe No. 3

Source: authors' development

According to the results of the analysis of the spectra of the flavour profile, the profile of fish paste made according to recipes No. 3 and No. 2 is most similar to the reference one. Thus, as a result of the conducted evaluation of ingredient compatibility in fish pastes using the flavor profile spectrum method, it was established that the formulation of the paste made from minced salted meat of two types of freshwater fish – Clarias catfish and trout – along with pink salmon milt and vegetables, enhances flavor and aromatic characteristics and improves the consistency of fish pastes. It was determined that salted pink salmon, carrots and onions are especially harmoniously combined with salted minced meat from fish meat.

Discussion

Fish products occupy an important place in human nutrition due to the content of essential amino acids, fatty acids, vitamins, micro- and macroelements. These nutritional factors in fish raw materials provide plastic and energy metabolism, can serve as a substance for medicines and have a preventive effect on many diseases (Bal-Prylypko *et al.*, 2024).

The authors improved the recipe composition of fish paste based on the meat of catfish, trout, onion, carrot, tomato paste, sunflower oil and spices. The organoleptic evaluation of the improved recipes of fish pastes based on the meat of catfish, trout, and pink salmon milt determined high quality indicators in terms of appearance, aroma, taste and consistency. These indicators are the best in the formulation with pink salmon milt, amounting to 24.1 ± 0.1 against 20.1 ± 0.4 points in the control and exceed other formulations based on catfish and trout meat (formulation No. 1 – 21.2 ± 0.5 and No. 2 – 21.9 ± 0.3). The developed recipe for fish pastes, according to organoleptic indicators, is consistent with the results of previous studies of fish pastes based on a combination of raw materials of freshwater and marine origin (Menchynska *et al.*, 2021). In these studies, the principle of combining raw materials was used not only in terms of the content of sources of biologically valuable protein and fatty acids of the ω-3 family but also in terms of the content of phospholipids. According to the data of A. Menchynska *et al.* (2021) the content of this fraction in capelin caviar lipids is up to 40%. The emulsifying properties of fish pastes are also provided by the introduction of sunflower oil, which, due to its high content of phospholipids, also exhibits emulsifying properties. According to the results of the current study, sunflower oil is present in the formulation from 12.2 to 12.7%, in contrast to 30% in the formulations of the above-mentioned authors. An additional

emulsifying effect in the current study is provided, according to the authors, by the properties of pink salmon milt. It can be assumed that these properties of fish paste formulation No. 3 are due to the taste properties of catfish meat and pink salmon milt.

According to the chemical composition, the protein level is higher in fish paste formulations with catfish, trout and pink salmon milt compared to those using only carp meat, as in the control. Thus, in the control formulation, the protein content is 13.05 ± 0.18, in the experimental formulations – from 13.78 ± 0.19 to 14.68 ± 0.16% of the total chemical composition. According to A. Menchynska *et al.* (2021), the protein content in fish pastes based on raw materials such as carp meat, silver carp meat and caviar, capelin caviar with vegetables and spices contains less protein – 12.68 ± 0.16 and 13.48 ± 0.19%. The highest amount of lipids was determined in the current study of the fish paste recipe with pink salmon milt – 34.13 ± 0.21%, in the study by A. Menchynska *et al.* (2021) based on fish caviar – 40.06±0.26%. These differences in chemical composition determine the difference in energy value. Thus, the highest energy value was obtained by a sample of fish paste with pink salmon milt – 365.77 kcal /100 g (Fig. 2) against the highest value of this indicator in pastes based on capelin and silver carp caviar – 411.26 kcal/100 g. The amount of lipids in carp, silver carp and capelin caviar is on average 3.91; 5.93; 13.88%. Pink salmon milt is characterised by a low lipid content – 2.10% (14, 15). Additionally, sunflower oil was used in the experimental paste formulations: based on catfish meat – 12.7%, based on fish caviar – 30%. Therefore, the lipid content in caviar-based fish pastes was higher. The protein-to-lipid ratio in the current study was 1:1.7 in the control, in samples No. 1, 2, 3 – 1:2.2, 1:2.40, and 1:2.33, respectively. These data are not consistent with the results of previous studies by the authors A. Menchynska *et al.* (2021) on fish pastes when using other raw materials, where this ratio in fish paste "Ikrynka" was 3.15; in "Zakusochna" – 2.72.

The analysis of the spectrum profile of fish pastes confirmed the data of the organoleptic evaluation and is consistent with the results of previous studies of fish pastes based on other raw materials – carp, silver carp and capelin caviar (Menchynska *et al.*, 2021). It has been determined that the formation of a "bouquet" of harmonious aroma and taste is influenced by the combination of fish, vegetable raw materials, sunflower oil, tomato paste, spices and, of course, the features of its preliminary preparation and the sequence of combination.

In the fish paste recipe developed by the authors, the organoleptic compatibility of the raw materials was determined. Theoretical studies have shown that sulfur-containing amino acids – methionine and cysteine – participate in the formation of a pasty, plastic and homogeneous consistency (Kunnath *et al.*, 2022). According to the results of research by A. Menchynska *et al*. (2021) fish raw materials, namely silver carp meat, contain a total amount of methionine with cystine of 3.35, carp caviar – 6.22, silver carp – 3.95, capelin – 5.24 g/100 g of protein, which ensures that the content of these acids in the recipe composition of experimental fish pastes is at a sufficiently high level – 7.98 and 3.82 g/100 g of protein. According to T. Lebska *et al*. (2021), the meat of the Clarias catfish is characterised by the presence of sulfur-containing amino acids at the level of 4.40 g/100 g of protein, which can contribute to the formation of the gel structure and provide a tender and juicy consistency of fish pastes. Thus, in the formation of a tender and creamy consistency of fish pastes, according to the authors of the current study, both a sufficiently high content of sulfur-containing amino acids and the presence of natural emulsifiers – phospholipids in the lipid composition of the raw material are involved.

Conclusions

Fish products occupy an important place in the structure of nutrition of the population of Ukraine, however, the level of its consumption does not correspond to the recommended levels for healthy nutrition. Therefore, the urgent task is to improve existing technologies for the production of fish products and expand the range. In this regard, the use of Ukraine's aquaculture resources, namely, catfish and trout, is of particular importance. In this aspect, an important place is occupied by multi-component food products, the creation of which is achieved by combining raw materials of different origins in order to provide humans with the necessary irreplaceable and replaceable nutritional factors. The technology of fish pastes allows creating such products based on the organoleptic compatibility of raw materials and their preliminary preparation (salting, grinding, heat treatment, etc.) and a specific sequence of mixing ingredients.

The authors conducted a study to improve the formulation of fish pastes based on the meat of the catfish, trout, pink salmon milt, vegetable raw materials and spices. The organoleptic assessment determined the compatibility of the raw materials. According to the nutritional value indicators, fish pastes are characterised by a high lipid content – 34.13 ± 0.21%, proteins – 14.68 ± 0.16% and energy value at the level of 364.77 kcal/100 g. Descriptors of the flavour spectrum were developed to characterise the aroma, taste, structure and consistency of fish pastes. Profile analysis based on the totality of structure and consistency indicators determined the highest quality of fish pastes based on the meat of the catfish and pink salmon milt compared with control samples and combinations of other raw materials. The influence of the content of sulfur-containing amino acids and phospholipids in raw materials on the formation of a tender and juicy consistency of fish pastes is discussed. Thus, the feasibility of expanding the range of food fish products based on Ukrainian aquaculture is proven. Further research will be aimed at determining the pre-treatment regimes of raw materials to ensure their safety and quality.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

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Оцінка якості рибних паст підвищеної біологічної цінності

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Анотація. Забезпечення населення України рибними продуктами набуває особливої актуальності, оскільки рівень їх споживання не відповідає рекомендаціям щодо оздоровчого харчування. Одним з напрямів, що здатен вирішити цю проблему, є розширення асортименту рибних паст, які за вартістю доступні широкому колу населення. Мета роботи полягала в удосконаленні рецептурного складу рибних паст на основі м'яса кларієвого сомика (*Clarias gariepinus* (Burchell, 1822)), форелі (*Salmo trutta fario*), молок горбуші (*Oncorhynchus gorbuscha*), рослинної сировини, а також в оцінці нових рецептур за комплексом органолептичних показників, профілю спектру флейвору, енергетичної цінності, фізико-хімічних методів досліджень: вміст вологи – методом висушування

зразка до постійної маси; вміст жиру – методом Сокслета; вміст білка – методом К'єльдаля; золи – спалюванням наважки. В результаті досліджень експериментально підтверджено доцільність поєднання у рецептурному складі рибних паст м'яса кларієвого сомика, молок горбуші та рослинної сировини. Розроблено три нових рецептури рибних паст на основі попередньо солених та подрібнених м'яса сомика, форелі і молок горбуші, пасерованої рослинної сировини (цибулі, моркви), олії соняшникової та спецій. Дослідження органолептичних показників та профілю спектру флейвору визначили найбільш високі показники консистенції у рибних паст з м'ясом сомика та молоками горбуші в порівняні з контролем та іншими рецептурами (9,5 ± 0,1 проти 8,5 ± 0,08 балів). За хімічним складом зразки рибних паст характеризувались високим вмістом вологи: 50,24 ± 0,17 в експериментальних рецептурах проти 61,62 ± 0,84 у контрольної, % відповідно. Вміст білку складав 14,65 ± 0,19 у пасті з молоками горбуші проти 13,05 ± 1,18 % у контрольної. Вміст ліпідів у нових рецептурах паст коливався від 32,12 ± 0,16 до 34,13 ± 0,21 проти 22,38 ± 0,17 %, що визначило високі показники їх енергетичної цінності: 347,11-365,77 проти 253,64 Ккал/100 г у контрольної. Результати досліджень показали доцільність поєднання у рецептурі рибних паст м'яса сомика з молоками горбуші та рослинною сировиною, що дозволить розширити асортимент якісної та корисної рибної продукції

Ключові слова: м'ясо сомика; молока горбуши; рослина сировина; органолептична оцінка; дескриптори; спектр флейвору; хімічний склад

ANIMAL SCIENCE AND FOOD TECHNOLOGY

Journal homepage: https://animalscience.com.ua/en
Animal Science and Food Technology, 16(2), 96-109
Received 05.01.2025 Revised 15.04.2025 Accepted 22.05.2025

UDC 663.22:663.252:663.256.2
DOI: 10.31548/animal.2.2025.96

The influence of oak alternatives on some quality characteristics of rosé wine

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Suggested Citation:
Tkachenko, D., Manoli, T., Nikitina, Ya., Menchynska, A., & Tkachenko, L. (2025). The influence of oak alternatives on some quality characteristics of rosé wine. *Animal Science and Food Technology*, 16(2), 96-109. doi: 10.31548/animal.2.2025.96.

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Abstract. Rosé wine has found its place in modern global society due to its perfect alignment with new consumption trends and lifestyle choices: less structured meals, a variety of cuisines from around the world, simple gastronomy, an interest in discovery, and the desire for immediate pleasure. Therefore, improving the organoleptic properties of table rosé wines is a relevant task. One way to influence the sensory characteristics of wine products is through treatment with finishing oak alternatives. The aim of this study was to enhance the technology of table rosé wine using oak alternatives, specifically experimental oak chips of Ukrainian production, compared to French counterparts. The study employed standard physicochemical and organoleptic analysis methods. The organoleptic and physicochemical quality indicators of table rosé wine made from Cabernet Sauvignon grapes grown in the Odesa Region (Ukraine) were studied. The conducted research identified the potential use of finishing oak chips as an additional beneficial method for diversifying the organoleptic characteristics of table rosé wines and enhancing specific characteristic descriptors of this type of wine at stages close to bottling. The stabilising effect of oak chips on colour compounds was determined, preventing their degradation, which is an important task in rosé wine production, without dominating the aroma. The highest scores in organoleptic evaluation were obtained by sample No. 103 (Oenofinisher Freshness Booster oak chips from the French manufacturer Seguin Moreau), which, in addition to the declared characteristics (enhancing fruity notes in the aroma), added nuances of pastry (biscuit and caramel), and sample No. 106 (oak chips of Ukrainian production from "Kont-2" LLC), which was characterised by pleasant fruity notes (mainly red currant, cranberry, and unripe strawberry) with additional biscuit undertones. As a result of this study, the technology for producing table rosé wine using oak chips has been improved. The organoleptic profiles of new Ukrainian oak alternatives have been described, allowing winemaking companies to enhance the quality of their wine products and influence wine styles. The production trial of rosé table wine using Ukrainian oak alternatives, which received the highest rating, was carried out at the winery First Winemaking Station

Keywords: technology; grapes; sensory analysis; phenolic complex; anthocyanins; tannins; acidity

Introduction

In recent years, there has been an increase in competition in the alcoholic beverages market, so the issue of improving the sensory characteristics of wine products is quite relevant because every year more and more consumers are inclined to choose high-quality wine. This is especially true for the production of table rosé wines, the rapid development of which has been observed since the mid-2000s. One of the priority areas for improving the technology of table rosé wines is the search for ways to improve organoleptic characteristics through the use of more economically viable alternatives to oak barrels, the cost of which remains consistently high.

According to the International Organisation of Vine and Wine, the demand for rosé wines has increased significantly over the past twenty years: statistics show a 25% increase in production (OIV, 2023). An analysis of rosé wine market trends conducted in over 30 countries predicts an increase in this wine category with an average annual growth rate of 5.5% until 2033 (Rosé wine market..., n.d.). One reason for the growing popularity of rosé wines is their versatility. Producers offer a wide range of styles, from light and crisp flavours to rich and complex, taking into account different preferences and making rosé wines go well with a variety of dishes. Rosé wines also appeal to

wine lovers with their bright, fruity flavours and attractive colours of varying intensities. In this context, wine producers are striving to improve the quality of rosé wines and better reveal their specificity. As P. Iván *et al.* (2025) point out, the main problem in the technology of rosé wines is their tendency to oxidation, which is manifested in the degradation of organoleptic indicators, primarily the appearance of unpleasant yellow, orange or brown shades in the colour and the loss of aroma. Therefore, the search for modern materials to slow down changes in sensory characteristics is relevant (Bai *et al.*, 2023). Tannins are considered to be one of the promising auxiliary materials for stabilising aromatic and colour characteristics, which can be used at different stages of production.

In addition, the Ukrainian wine industry faces the problem of insufficient information on the characteristics of oak alternatives, which complicates the selection of the optimal material for the production of rosé wines. Producers of oak alternatives often do not provide complete data on the origin of the wood, which can affect the final sensory profile of the wine. This requires the creation of detailed technical characteristics of oak alternatives and the development of recommendations for their use in winemaking. The use of oak alternatives can also be an effective tool for improving the colour stability of rosé wines. Phenolic compounds contained in oak chips are able to interact with anthocyanins, which are the main pigments responsible for the colour of rosé wines. This process can help stabilise the colour range and prevent the loss of hue brightness during ageing and storage.

The sensory profile of rosé wines can vary significantly depending on the type of oak chips used. For example, lightly toasting oak chips helps to enhance floral and fruity notes, while more intensive toasting can impart notes of chocolate, spices or even nuts to the drink (Marr, 2024). This opens up wide opportunities for winemakers to create a unique style of rosé wine adapted to the tastes of consumers. Therefore, the need to find modern technological solutions to stabilise the colour, aroma and overall quality of rosé wine is extremely urgent. The use of oak alternatives is one of the promising areas in this area but requires thorough scientific research.

Research into the effectiveness of oak alternatives in the production of rosé wines will allow producers to choose optimal processing methods, which will help improve the quality and competitiveness of Ukrainian wines on the global market. At the current stage of development of Ukrainian winemaking, the search for innovative solutions is key to the sustainable development of the industry (Bezhenar, 2024). In this context, scientists point to the need to improve the technological processes of wine production (Kormyshkina, 2025). Analysis of modern scientific research indicates that the use of oak alternatives in winemaking is an important tool for modifying the physicochemical and sensory characteristics of wine. In particular, the study by C. Leborgne *et al.* (2022) on the influence of different types of oak wood on the organoleptic profile of rosé wines confirms that oak chips can contribute to the stabilisation of the colour of rosé wines through the interaction of phenolic compounds with anthocyanins, which provides resistance to oxidation. An important aspect is the cost-effectiveness of using oak alternatives. Oak chips allow winemakers to significantly reduce production costs while maintaining high organoleptic characteristics of the wine. This is especially important for small and medium-sized wineries that do not have the opportunity to invest significantly in oak barrels. Thus, the analysis of the literature demonstrates that oak alternatives are an effective tool for improving the characteristics of rosé wines.

This study aimed to investigate the impact of using an oak alternative on the physicochemical and organoleptic characteristics of rosé wines. To achieve this aim, the following tasks

were set: to identify the impact of oak chips on the physicochemical characteristics of dry table rosé wine; to compare the declared organoleptic style of Seguin oak chips Moreau (France) with actual data, as well as to describe the organoleptic profile of oak chips from "Kont-2" LLC (Ukraine) when using new oak alternatives on the market.

Materials and Methods

Sensory research was conducted at the Odesa National University of Technology in the educational and scientific laboratory of sensory analysis, which is accredited in accordance with the requirements of DSTU EN ISO/IEC 17025:2019 (2021); physicochemical research was conducted in the accredited laboratory of LLC "First Winemaking Station". During the study, dry rosé table wine from the Cabernet Sauvignon grape variety, produced by LLC "First Winemaking Station", was used as the material (Velykodolynske, Odesa Region) in 2023. The research was conducted in April-June 2024. Wine materials for the research were prepared according to the following technological scheme: grape reception → processing with sorting → crushing with separation of the stems on a roller crusher and sulphitation → short-term infusion of the must on the pulp with cooling and introduction of an enzyme preparation → pressing of the pulp with selection of the must for the production of wine in an amount of no more than 60 dal (decalitre) from 1 ton of grapes → clarification of the must by settling with treatment with gallic tannin and a complex preparation consisting of bentonite, plant protein and PVPP (polyvinylpolypyrrolidone) → fermentation of the clarified must on a PYC (pure yeast culture) with temperature regulation → after the end of fermentation and the first racking, ageing on a thin layer of yeast sediment for six months → treatment for stabilisation. Oak chips were added to the wine materials a month before bottling. The doses were selected as average values from the manufacturer's recommended ranges (Fig. 1). The test and control samples were kept at a temperature of 15°C.

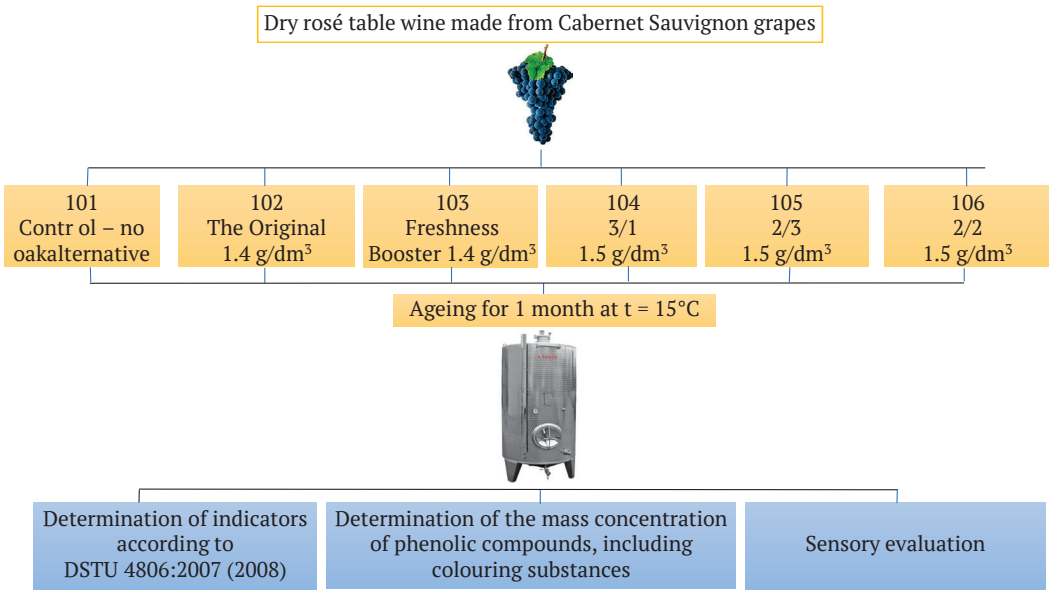

Figure 1. Experimental procedure scheme

Source: developed by the authors

To assess the impact of oak alternatives, the following were used:

➢ control: dry rosé table wine from Cabernet Sauvignon grapes (sample No. 101);

➢ oak chips from Seguin Moreau (France): Oenofinisher the Original (sample No. 102); Oenofinisher Freshness Booster (sample No. 103) (Oenofinisher..., 2021);

➢ oak chips from "Kont-2" LLC (Ukraine): code 3/1 (sample No. 104); code 2/3 (sample No. 105); code 2/2 (sample No. 106).

A description of the oak alternatives used in the study is given in Table 1. When harvesting wood chips from holm oak and pedunculate oak, which grow in Ukraine, wood with an increased content of aromatic compounds is selected.

Table 1. *Description of oak alternatives used in the study*

Oak alternative name/code	When to add	Dosage g/dm ^{3}	Contact time	Oenological task
France, Seguin Moreau				
Oenofinisher the Original	End of ageing (ageing before bottling) (fermentation possible)	0.5-2 g/dm ^{3}	1 week	Candied fruit, vanilla, roundness in the mouth
Oenofinisher Freshness Booster	End of the ageing or alcoholic fermentation process	0.7-1.5 g/dm ^{3}	1-2 weeks	Distinctive notes of exotic fruits
Ukraine, "Kont-2" LLC				
3/1	During the fermentation or ageing stage	1-4 g/dm^3	3-6 months	Imparting pronounced woody, vanilla and spicy notes, strengthening the structure of the drink
2/3	At the beginning of ageing or before the final blend	1-3 g/dm^3	2-5 months	Softening tannins, adding caramel and sweet nuances, rounding out the taste
2/2	During ageing or at the final stage before bottling	0.5-2 g/dm^3	1.5-4 months	Increasing the complexity of the taste, adding nutty and chocolate nuances, harmonising the overall profile

Source: developed by the authors

During the research, generally accepted standardised physicochemical and organoleptic analysis methods were used, enabling the assessment of changes in the structure, aromatic profile and general sensory characteristics of wine after contact with different types of oak chips: the mass concentration of sugars in the must was determined according to DSTU 7669:2014 (2015); the mass concentration of titrated acids in the must and wine according to DSTU 4112.13:2002 (2003); the pH value in the must according to DSTU 6045:2008 (2009); the pH value in the wine according to DSTU 4112.24:2002 (2003); the volume fraction of ethyl alcohol according to DSTU 4112.3:2002 (2003); mass concentration of sugars in wine materials in terms of invert sugar according to DSTU 4112.5:2002 (2003); mass concentration of volatile acids according to DSTU 4112.14:2002 (2003); mass concentration of sulfurous acid according to DSTU 4112.25:2002 (2003); mass concentration of the reduced extract according to DSTU 4112.14:2002 (2003); determination of the mass concentration of phenolic, including colouring substances (anthocyanins) – by the colourimetric method according to DSTU 4112.41:2003 (2004); modern scoring systems for assessing wine quality according to the requirements of the International Organisation of Vine and Wine (OIV, 2021); methods for creating a flavour spectrum according to DSTU ISO 6564:2005 (2006). To conduct organoleptic studies, 7 sensory analysis experts were involved, whose panel was pre-calibrated. The study adhered to the ethical principles outlined in the Declaration of Helsinki (1964) regarding research involving human subjects.

In the process of analysing the obtained experimental data (repetition rate 3), statistical processing was carried out using the PanelCheck V1.4.2 program and the method for creating a flavour spectrum, according to DSTU ISO 6564:2005 (2006), which ensured the objectivity and reliability of the results obtained; developed by Principal Component Analysis (PCA) map. 150 dal of wine materials were produced using improved technology.

Results and Discussion

According to the results of the analysis of the control and experimental samples, it was found that the use of oak alternatives does not significantly affect the physicochemical parameters specified in DSTU 4806:2007 (2008), which are within the error limits provided for by the standard and correspond to modern world views on the values of these parameters in rosé wines. The key factor that affects the quality of wines and distinguishes rosé wines from white and red wines is the content of phenolic substances, including colouring substances (Iazzi *et al.*, 2019; Del Alamo-Sanza *et al.*, 2021). Wine quality assessment is based on sensory and physicochemical analyses (Bilko, 2019; Zhao *et al.*, 2022; Paissoni *et al.*, 2022). In the sensory evaluation of rosé wines, wine quality indicators, such as colour and taste, are significantly influenced by the phenolic component (Bilko *et al.*, 2019; Rinaldi *et al.*, 2021). Table 2 presents the values of the mass concentration of phenolic and colouring substances of the control and experimental samples of dry rosé table wine from Cabernet Sauvignon grapes of the 2023 harvest.

Table 2. *Characteristics of the phenolic complex of the control and experimental samples from Cabernet Sauvignon grapes of 2023*

Oak alternative name	Mass concentration, mg/dm³	
	Phenolic substances	Colouring substances
Control 101	375	14
No. 102	350	20
No. 103	355	24
No. 104	370	18
No. 105	375	22
No. 106	395	16

Source: developed by the authors

The data in Table 2 indicate the following: the mass concentration of phenolic substances in the control and experimental samples is in the range from 350 to 395 mg/dm³, with a mass concentration of colouring substances in the range from 14 to 24 mg/dm³. As noted by M. Bilko (2019), rosé wines can be divided into two types by style – European and domestic. The European style is characterised by a content of phenolic substances from 290 to 478 mg/dm³, including colouring substances 6-44 mg/dm³. The domestic style has a higher mass concentration of phenolic substances 532-726 mg/dm³, including colouring substances 50.6-64.5 mg/dm³. In accordance with the indicated styles, the control and experimental samples belong to the European style. The values of the mass concentration of colouring substances of the control and experimental samples are in the average or closer to the lower limit, which is associated with the six-month ageing of wine materials on a thin layer of yeast sediment and, accordingly, the absorption of anthocyanins by the yeast mass. Comparing the experimental samples with the control, only in sample No. 106 the content of phenolic substances increased. Sample No. 105 has the same mass concentration of phenolic substances as the control. Samples No. 102, No. 103, No. 104 have lower values of this indicator than in the

control sample. Such differences may be associated with the origin of the raw materials, the degree of toasting and the duration of contact with oak alternatives.

The mass concentration of colouring substances of the experimental samples compared to the control was higher from 14% to 1.7 times and in ascending order was: for sample No. 106 – 14%, for sample No. 104 – 28.5%, for sample No. 102 – 1.4 times, for sample No. 105 – 1.6%, for sample No. 103 – 1.7 times, and their percentage relative to the total concentration of phenolic substances is: for control sample No. 101 – 3.7%, for sample No. 106 – 4.1%, for sample No. 104 – 4.9%, for sample No. 102 – 5.7%, for sample No. 105 – 5.9%, for sample No. 103 – 6.8%. These data indicate that even short-term contact with an oak alternative "stabilises" colourants, which is a positive fact, especially for European-style wines with low mass concentration of colourants. The effect of oak alternatives on the organoleptic indicators of the control and experimental samples is shown in Figure 2, and the generalised profilogram of the experimental samples compared to the control is shown in Figure 3.

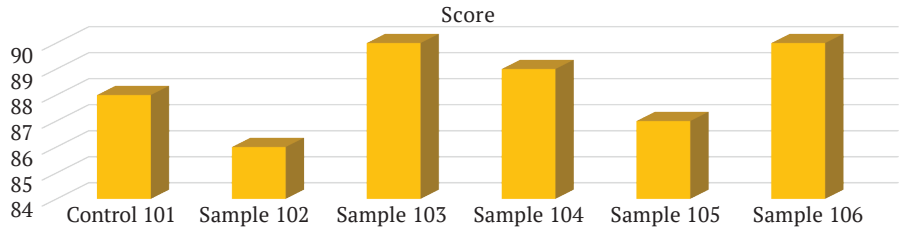

Figure 2. Score of test samples compared to control

Source: developed by the authors

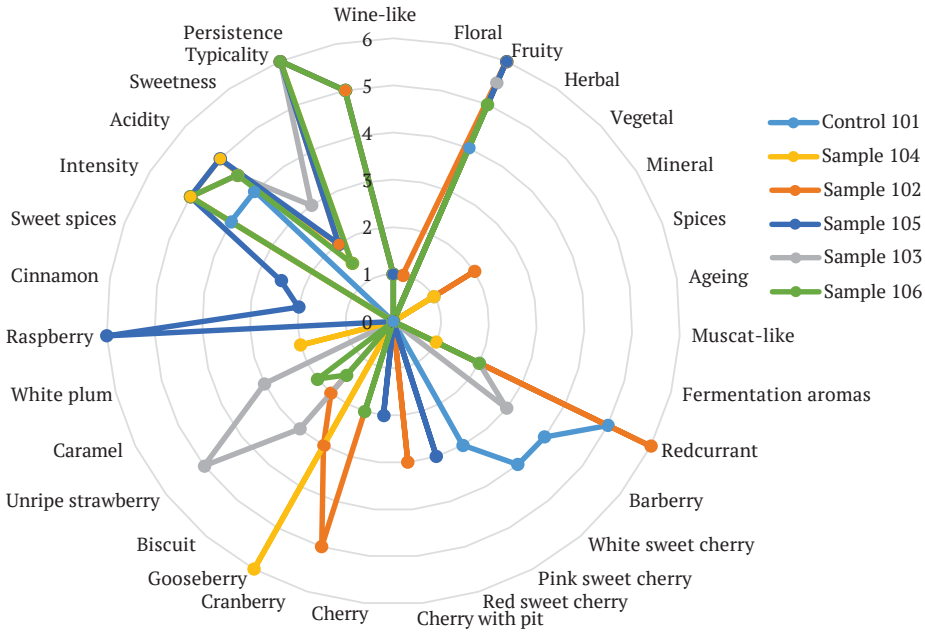

Figure 3. Generalised profilogram of test samples compared to control

Source: developed by the authors

The results of the sensory evaluation by the scoring method and the flavour method showed the following. Control sample No. 101 received 88 points and was characterised by an intense fruity aroma (4 out of 7), with notes of currant, barberry, white cherry and pink cherry. Acidity and intensity of taste are above average (5 points out of 7). Sample No. 102 (oak chips from a French producer), which received the lowest score (86 points), according to the characteristics of the producer, was supposed to impart sweet notes of fruit and pastries (candied fruit, vanilla) and roundness to the wine. Experts found an increase in fruit aromas, with mineral, floral and wine nuances combined with enhanced notes of currant. Aromas of cranberry, gooseberry, notes of biscuit and cherry with pit were added. In general, the aromatic qualities are close to those declared by the producer. The perception of raw wood notes in the aroma slightly reduced the score. The taste is quite intense, with a long aftertaste, lively acidity, and a slight sweetness. The colour is medium-intensity and has cranberry hues. Considering that medium doses of wood chips were chosen during the experiment, it is worth increasing the dosage for this oak alternative.

Sample No. 103 (wood chips from a French producer) received the highest score (90 points), according to the manufacturer's specifications, the wood chips should enhance fruit and/or floral notes and enhance varietal aromas. Experts identified the dominant aroma of unripe strawberries, notes of biscuit, caramel and barberry at a level below average, with delicate nuances of currant. The duration of the taste and typicality of almost the maximum level with sweetness of medium intensity. Colour: medium intensity, salmon shades. The manufacturer does not declare in its specifications the appearance of pastry notes (biscuit and caramel), which appeared during contact with the wood chips. To reveal all the aromatic and taste nuances of this oak alternative, it is worth increasing the dosage or duration of contact. Samples No. 104, No. 105, No. 106 (wood chips from a Ukrainian producer) are experimental. They received scores of 89 (on par with the control), 87 and 90 points, respectively.

Sample No. 104 was characterised by pronounced aromas of gooseberry, with nuances of white plum and currant of low intensity in the background. In general, the fruity aroma was enhanced. Taste: intensity, typicality, acidity and longevity at a high level. The colour is less intense than other samples, the shade is greyish-salmon. Sample No. 105 was characterised by pronounced raspberry notes, with added notes of red cherry, sour cherry, sweet spices, and cinnamon compared to the control. Intensity, typicality and duration are close to maximum, with a slight sweetness. The colour is quite intense, raspberry, tannins are aggressive and most pronounced. Sample No. 106 also had the highest score (90 points). The taste qualities were noted at a high level: intensity, acidity, typicality and longevity with a barely noticeable sweetness. Characterised by moderate notes of currant, cranberry, unripe strawberry and biscuit. The colour is medium intensity, raspberry-salmon. The tannins are bright and pleasantly expressed (Fig. 4).

As can be seen from Figure 4, sample No. 101 (control) is significantly different from the other samples and is located in the upper right part of the map. This means that it has unique sensory properties without the influence of oak chips. Sample No. 102 using French oak chips Oenofinisher the Original, Seguin Moreau is also distant from the other samples. This type of oak chips shows higher values of sweetness and longevity aftertaste that distinguishes it from the control sample and other processing options. Sample No. 103 Oenofinisher Freshness Booster is closer to samples No. 104, No. 105, No. 106, which may indicate some similarity in the impact on sensory properties, but has increased acidity, which confirms its name – it adds "freshness". Samples with Ukrainian oak chips No. 104, No. 105, No. 106

are grouped together, which have a moderate impact on fruit notes and typicality, but the difference between them is small, which confirms their close position on the PCA map. So, French oak chips have a more differentiated impact on the sensory profile: Oenofinisher the Original enhances sweetness and aftertaste. Oenofinisher Freshness Booster adds acidity and "freshness". Ukrainian oak chips have a similar effect, but it differs from the control sample and French variants. The PCA map well illustrates the grouping by sensory characteristics, which helps to choose the optimal variant of oak chips to achieve the desired bouquet.

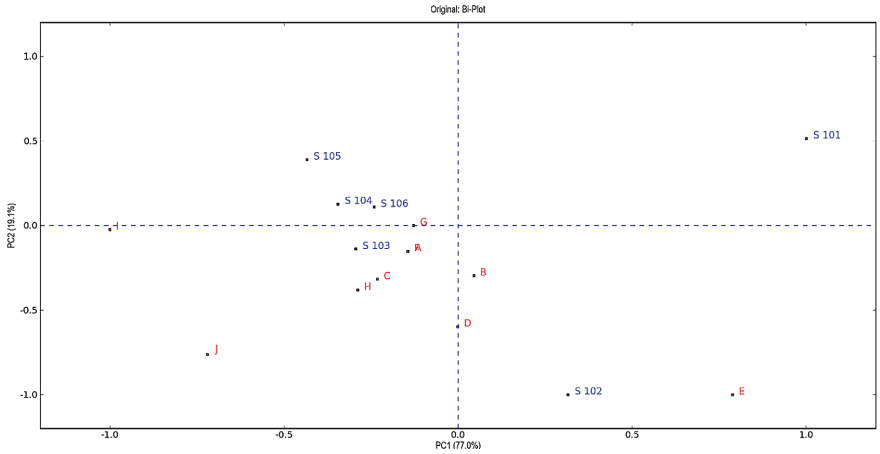

Figure 4. PCA map of samples depending on descriptors and studied samples

Note: Attribute A is the wine aroma, which is characterised by typical notes of fermentation and ageing. Attribute B is the floral aroma, which gives the wine tenderness and sophistication. Attribute C is the fruity aroma, which adds freshness and brightness to the drink. Attribute D is the minerality, which is expressed in the form of light salty or flinty shades. Attribute E is the aroma of currants, which gives the wine a pleasant sourness and berry freshness. Attribute F is the intensity of taste, which reflects the overall expressiveness of the taste and aroma of the wine. Attribute G is the acidity, which determines the level of freshness and balance of the wine. Attribute H is the sweetness, which can vary from barely perceptible to rich. Attribute I is the typicality, which demonstrates the correspondence of the wine to its style and region. Attribute J is the longevity, which characterises the length of the aftertaste and its development after a sip

Source: developed by the authors

In conclusion, it should be noted that the use of finishing oak chips allowed to preserve and, in some cases, to enhance the dominance of fruit aromas. In particular, the treatment with chips, due to its rapid effect, stabilises the colour of the wine without giving it a dominant wood character. The obtained experimental wine samples correspond in colour to the experimental studies of M. Bilko (2019). The colour of rosé table wines had a wide range of shades: light flesh, pink, raspberry with light coral shades, a slice of fresh salmon. The rosé wine samples, after contact with oak chips, received characteristic descriptions of wines aged in oak barrels, acquiring biscuit, caramel and spicy notes. Ageing (ageing before bottling) rosé wines in the presence of oak chips may be a good option for giving unusual notes to this type of wine. Authors I. Nunes *et al.* (2020) also found in their study that oak alternatives can significantly improve the aromatic characteristics of rosé wine. They note that light toasting of oak chips helps to enhance floral and fruity notes, while medium and heavy toasting add

notes of chocolate, spices and nuts to the wine. Similar results were obtained by researchers M. Puyo *et al.* (2023), who noted that the use of oak alternatives could be part of a biosecurity strategy for rosé wines. Additionally, a study by M. Hernández-Carapia *et al.* (2023) showed that the use of American oak chips in the ageing process of rosé wine contributes to the improvement of its sensory profile, in particular, increasing the intensity of fruit aromas and harmonising the taste balance. This is consistent with the work of other authors such as D. Stegarus *et al.* (2021), I. Liga & Y. Kotseridis (2024), who emphasise the importance of choosing the right oak alternative to achieve the desired wine characteristics. Thus, the use of oak alternatives, especially with careful selection of the origin of the chips and the degree of toasting, offers winemakers a promising way to enhance the organoleptic complexity and stability of rosé wines, providing desirable nuances that resonate with changing consumer preferences.

Conclusions

The use of oak alternatives is an effective method of improving the quality of rosé wines. French Oak Alternatives Seguin Moreau provide a more pronounced effect on the sensory profile of wine, while Ukrainian alternatives from "Kont-2" LLC showed competitive results. It was found that Ukrainian oak alternatives can be used on a par with French ones, but it is necessary to improve the technical descriptions by manufacturers for a better understanding of their characteristics. At the same time, it was found that not all manufacturers of oak alternatives provide sufficiently complete information about the features and origin of oak, which makes it difficult to make an informed decision about its use. Oak chips do not significantly affect the physicochemical indicators defined by DSTU 4806:2007. All values remained within the permissible limits. However, an increase in the mass concentration of phenolic and colouring substances was noted, contributing to the stabilisation of the colour of the wine. The greatest effect on the phenolic complex was observed in sample No. 106, where the concentration of phenolic substances was higher than in the control sample.

Tasting score on a 100-point scale showed that: the control sample received 88 points with pronounced fruity notes. The French samples had different effects: Oenofinisher the Original (86 points) provided sweet notes of fruit and pastries, while Oenofinisher Freshness Booster (90 points) enhanced the fruity and floral notes. Ukrainian samples received scores from 87 to 90 points, with pronounced fruity and spicy notes. Sample No. 106 had the highest score (90) due to the harmonious combination of acidity, flavour intensity and aftertaste. Analysis using the flavour spectrum method showed that: French oak alternatives had a more differentiated impact on the sensory profile. Oenofinisher the Original enhanced the sweetness and aftertaste, while Oenofinisher Freshness Booster added freshness and increased acidity. Ukrainian oak alternatives had a similar effect, but more harmonious, without excessive oak influence. PCA map analysis showed that the control sample was significantly different from the experimental ones, without the influence of oak chips. French oak alternatives show more pronounced changes in sweetness and aftertaste, while Ukrainian oak alternatives are grouped closer to each other, having a moderate influence on fruit notes. In general, the use of oak chips allows to preserve and enhance fruit aromas, stabilise colour and give rosé wines additional nuances without dominating the woody characteristics. Further research should be aimed at optimising the dosage and contact time of oak alternatives with wine, as well as developing recommendations for their use in various technological processes of winemaking.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

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Вплив дубових альтернатив на деякі якісні характеристики рожевого вина

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Анотація. Рожеве вино знайшло своє місце у сучасному світовому суспільстві завдяки ідеальному узгодженню з новими тенденціями споживання та способу життя: менш структуровані страви, різноманіття кухень з усього світу, проста гастрономія, інтерес до відкриття нового та прагнення отримання негайної насолоди. Тому підвищення

органолептичних властивостей столових рожевих вин постає актуальним завданням. Одним зі способів впливу на сенсорні характеристики винопродукції є обробка фінішними дубовими альтернативами. Мета роботи полягала в удосконаленні технології виробництва рожевого столового вина за допомогою дубової альтернативи на прикладі експериментальної тріски українського виробництва у порівнянні з французькими аналогами. У роботі використовувались загальноприйняті стандартизовані фізико-хімічні та органолептичні методи аналізу. Досліджено органолептичні та фізико-хімічні показники якості столового рожевого вина з винограду сорту Каберне-Совіньйон, виробленого в умовах Одеської області (Україна). Проведеними дослідженнями виявлено можливість використання фінішної дубової тріски як додаткового корисного способу урізноманітнення органолептичних характеристик столових рожевих вин та підсилення окремих характерних дескрипторів для цього типу вина на етапах, близьких до розливу готової продукції. Визначено стабілізуючий ефект дубової тріски на барвні речовини, запобігання деградації яких є важливим завданням при виробництві рожевих вин, без домінації в ароматі. Найвищі бали органолептичної оцінки одержав зразок №103 (тріска Oenofinisher Freshness Booster французького виробника Seguin Moreau), який окрім заявлених характеристик (розкриття фруктових нот в ароматі) додав нюанси випічки (бісквіту та карамелі), та зразок №106 (тріска українського виробника ТОВ «Конт-2»), який характеризувався приємними фруктовими нотами (переважно порічки, журавлини, нестиглої полуниці) та з додатковими відтінками бісквіту. У результаті проведеної роботи удосконалено технологію виробництва столового рожевого вина за допомогою дубової тріски; описані органолептичні профілі нових дубових альтернатив українського виробництва, що дозволить виноробним компаніям покращувати якість винопродукції та впливати на стилістику вин. Проведено виробничу апробацію технології виробництва рожевого столового рожевого вина за допомогою дубової альтернативи українського виробництва, яка отримала найвищий бал, на винзаводі ТОВ «Перша виноробна станція»

Ключові слова: технологія; виноград; сенсорний аналіз; фенольний комплекс; антоціани; таніни; кислотність

ANIMAL SCIENCE AND FOOD TECHNOLOGY

Journal homepage: https://animalscience.com.ua/en
Animal Science and Food Technology, 16(2), 110-128
Received 20.12.2024 Revised 19.04.2025 Accepted 22.05.2025

UDC 664.68
DOI: 10.31548/animal.2.2025.110

The impact of active packaging and nanocoatings on the safety and shelf life of dairy products

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Suggested Citation:
Sattarov, K., Eshmurodov, D., Mamatkulova, M., Julbekov, I., & Kharsika, I. (2025). The impact of active packaging and nanocoatings on the safety and shelf life of dairy products. *Animal Science and Food Technology*, 16(2), 110-128. doi: 10.31548/animal.2.2025.110.

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Abstract. The aim of the study was to identify effective methods for maintaining the quality and safety of dairy products through the use of active packaging and nanotechnology. The methodology included an analysis of regulatory documents and current trends in packaging technologies, as well as experimental studies using control and experimental groups. The study found that milk and cottage cheese packaged in standard cardboard packaging with an inner layer of aluminium foil showed an average moisture content of 88.2 ± 0.5% and a redox potential of 185 ± 2 mV. In the group with active packaging containing antioxidant components, the moisture content was 87.5 ± 0.4%, and the oxidation reduction potential (ORP) was reduced to 175 ± 1 mV. Packaging with silver nanoparticles showed the highest efficiency, where the moisture content of milk and cheese was 86.7 ± 0.3%, and the ORP reached 170 ± 1.5 mV, indicating a reduction in the level of oxidative processes and improved product preservation. In addition, the study found that milk and cheese stored in active packaging and packaging with nanofilm showed significantly better organoleptic characteristics compared to control samples. In particular, the taste, smell, texture, and colour received higher scores on a scale from 1 to 5. For the control group, the average taste score was 3.2 ± 0.3, for active packaging – 4.0 ± 0.2, and for nanofilm – 4.7 ± 0.1. Similar results were recorded for odour (3.2 ± 0.3, 4.1 ± 0.2 and 4.8 ± 0.1, respectively), texture (3.1 ± 0.4, 4.0 ± 0.3 and 4.6 ± 0.2), and colour (3.0 ± 0.2, 4.2 ± 0.1 and 4.7 ± 0.1). These data indicated a significant improvement in the organoleptic characteristics of dairy products stored in active packaging and packaging with nanofilm compared to control samples. The practical significance of the study was to develop recommendations for dairy producers on the choice of packaging materials depending on the shelf life and conditions of sale. The results obtained could be used in the food industry to introduce innovative packaging technologies, as well as serve as a basis for further research in the field of food safety and the development of environmentally friendly packaging material

Keywords: innovative technologies; industrial quality; nanomaterials; antioxidants; antimicrobial properties

Introduction

The problem of the impact of active packaging and nanocoatings on the safety and shelf life of dairy products is relevant, as dairy products are among the most susceptible to spoilage due to high sensitivity to microbiological, chemical and physical changes. In particular, the development of new packaging technologies, such as active packaging and the use of nanocoatings, can significantly improve the freshness of dairy products, reduce spoilage losses and extend shelf life. Such innovative packaging methods can also help reduce food waste, which is an important part of global initiatives to conserve resources and sustainability, and improve product safety through the ability to actively interact with the environment by regulating humidity, oxygen levels or the release of antimicrobial agents.

This problem has been studied by scientists, in particular, S. Verbytskyi *et al*. (2024) explored innovative solutions to extend the safe shelf life of dairy products, including the use of advanced packaging technologies such as active packaging and nanocoatings to improve product safety and reduce spoilage. The authors emphasised the importance of innovative packaging approaches to improve the quality and shelf life of dairy products in a competitive market. In the research of Y. Verkhivker *et al.* (2023) and M. Klein *et al.* (2024) examined the use of C-PET consumer polymer containers in food production, highlighting effectiveness in

maintaining food quality and safety. The researchers discussed the benefits of polymer-based containers for extending the shelf life of dairy and other products, providing a more efficient packaging solution for the food industry. O. Rechun & O. Peredriy (2021) explored active and smart packaging for food, in particular its impact on food quality and safety, as well as the informative function of packaging. The scientists analysed the main technologies used in active and smart packaging systems and evaluated the advantages and disadvantages of such approaches, including the ability to reduce food loss and improve freshness. Researchers L. Kucher *et al.* (2021) studied the state and prospects of implementing the Hazard Analysis and Critical Control Point (HACCP) system in Ukraine to comply with EU food safety directives. The authors analysed the current challenges and opportunities for adapting Ukrainian standards to European food safety requirements, focusing on the need to improve safety legislation and practices. The peculiarities of the functioning of the food market in the context of the war in Ukraine were studied by L. Kvasnii *et al.* (2024). The authors analysed the negative impact of hostilities on food supply and production, as well as on the safety and stability of food systems in Ukraine during the crisis.

In addition, Y. Gadaieva *et al.* (2024) studied the environmental safety of food packaging, focusing on the importance of environmentally friendly materials and technologies in the packaging process to reduce environmental impact. The researchers discussed the prospects of using such materials in food production, in particular dairy products, to ensure safety and maintain ecological balance. L. Hortseva *et al.* (2020) identified the risks associated with the migration of toxic substances from packaging materials to food, which can lead to contamination and hazards to human health, and proposed strategies to control and minimise such risks. The authors focused on analysing the potential human health hazards arising from the use of hazardous packaging materials and proposed strategies to minimise such risks. P. Kapitala & G. Khimicheva (2021) assessed the quality and safety of dairy products in accordance with HACCP principles and ISO 22000:2019 (2019). The author investigated how the application of these standards can help ensure an appropriate level of food safety and meet the requirements of international certification for quality control at all stages of production. In the study, M. Bazhal & T. Koutchma (2022) identified the risks associated with non-compliance with food safety standards, in particular due to outdated technologies and insufficient infrastructure development in Ukraine, and discussed ways to overcome risks with the help of scientific and technological progress to improve global food security, namely the modernisation of infrastructure to ensure effective inspection and quality control of products.

Despite the above studies, these authors did not sufficiently investigate the impact of the combination of different types of active packaging (antimicrobial, antioxidant, absorbent) on dairy products, as well as the interaction with nanocoatings. In addition, insufficient attention has been paid to the impact of these technologies on the long-term preservation of organoleptic characteristics, such as taste, smell, and texture of dairy products. The aim of this study was to determine the effectiveness of active packaging and nanocoatings in improving the shelf life and safety of dairy products. The objectives of the study were to analyse the types of active packaging and the mechanism of action on dairy products, assess the impact of nanocoatings on the shelf life and safety of dairy products, and investigate the impact of active packaging and nanocoatings on the organoleptic characteristics of dairy products, including taste, smell, and texture.

Materials and Methods

The types of packaging used for the study were active packaging with antioxidants, packaging

with silver nanoparticles, and cardboard packaging with barrier materials, which met the requirements of Regulation (EC) No. 1935/2004 of the European Parliament and of the Council "On Materials and Articles Intended to Come into Contact with Food" (2004). In addition, the packaging was compliant with Regulation (EU) No. 1169/2011 of the European Parliament and of the Council "On the Provision of Food Information to Consumers" (2011), providing a clear indication of the presence of nanomaterials in food through the appropriate "nano" labelling in the list of ingredients. The first step was to analyse the use of active packaging and nanotechnology in the food industry. The types of active packaging and mechanisms of action were reviewed, including antimicrobial, antioxidant and absorbent packaging, as well as nanomaterials used in dairy packaging, such as silver and copper nanoparticles, metal oxides (zinc oxide (ZnO) and titanium dioxide (TiO_2)), and cardboard packaging with barrier materials.

A survey was conducted to assess the attitudes of food industry experts towards the introduction of active packaging and nanocoatings in dairy production. The study involved 50 food industry experts aged 25 to 60, 60% of whom were men and 40% women. The group of food industry experts included individuals with experience in the food industry, particularly in dairy production, and knowledge of the implementation of active packaging and nanocoatings. The survey was conducted over a two-week period in the format of an online questionnaire via the Google Forms platform. The survey was conducted in accordance with the Code of Ethics of the American Sociological Association (2018). The questionnaire contained 15 questions. The results allowed determining the general attitude of respondents to the use of active packaging and nanocoatings in the dairy industry, as well as identifying the main factors that affect trust and willingness to consume such products.

The study was conducted at Dnipro Dairy Plant LLC, a company specialising in the production of pasteurised milk and cottage cheese. The study was conducted between June and August 2024. The following specific samples were selected for the experiment: pasteurised milk with a fat content of 3.2% and cottage cheese with a fat content of 5%. The milk was obtained directly from the production line of Dnipro Dairy Plant LLC, and the cottage cheese was obtained from a series of products produced at the enterprise for testing for organoleptic and physicochemical parameters. The number of samples for the study was 60 units, namely 30 units of pasteurised milk and 30 units of cottage cheese, which were divided into three groups for further storage and testing. The calorie content of milk was 60 kcal per 100 ml; 3.2 g – fat, 3.3 g – protein, 4.7 g – carbohydrates. For cottage cheese, the calorie content was 120 kcal per 100 g; 5 g – fat, 15 g – protein, 1 g – carbohydrates. Milk and cottage cheese were stored in different types of packaging. The temperature was maintained at 4°C by a Model X-200 refrigerator with automatic temperature control, and the humidity was regulated at 70-80% by a HygroMaster 3000 hygrometer. The shelf life of the products was 15 days. During this period, the organoleptic characteristics were regularly monitored and possible changes in the composition of the products were identified. The number of samples of each type of product tested was 60 units (20 units per group). The first group (control) was stored in standard packaging without additional protective properties. The standard packaging for milk and cheese consisted of cardboard packages with an inner layer of 6.5 μm thick aluminium foil produced by Dnipro Dairy Plant LLC, which provided protection against light, oxygen, and moisture. The second group was placed in active packaging, which contained antimicrobial and antioxidant components

that can slow down bacterial growth and oxidative processes. The active packaging contained antimicrobial components, such as silver nanoparticles (10 ppm) and zinc oxide (0.05%), as well as antioxidants, such as vitamin E (0.02%) and polyphenols (0.1%), which slowed bacterial growth by disrupting microbial cell membranes and prevented the oxidation of fats by absorbing free radicals. The third group included samples coated with a nanofilm containing silver nanoparticles (up to 0.5%) and metal oxides (ZnO and TiO_2 in concentrations up to 1%), which provided antimicrobial effects and barrier properties against the penetration of oxygen and microorganisms, creating a barrier to the penetration of microorganisms and oxygen. The packaging used silver nanoparticles with a size of 10-50 nm and metal oxides (ZnO, TiO_2) with a particle size of 20-100 nm, which were applied by plasma spraying technology to the polymer base, providing a uniform coating, the materials were produced by NanoPack Solutions Ltd.

To evaluate the impact of different types of packaging during the experimental period, measurements of physicochemical, microbiological and organoleptic parameters were carried out. Specialised equipment was used to measure the physicochemical and microbiological characteristics of dairy products. The pH level was measured using an Orion pH meter, model 3 STAR, which provided an accuracy of up to 0.01 pH units. The acidity of dairy products was determined by acid-base titration with 0.1 n NaOH solution until a stable pink colour appeared, using phenolphthalein as an indicator. The moisture content was determined by drying in an oven at 105°C for 6-8 hours until a stable weight value was reached. The oxidation reduction potential (ORP) was measured using a Hanna redox meter model HI 9147. All measurements were carried out under standard laboratory conditions with a temperature of 20-22°C and humidity of 60-65%.

The organoleptic characteristics were assessed by a tasting panel of three experts with experience in the food industry who evaluated the organoleptic characteristics of dairy products. The evaluation criteria included taste, smell, texture and colour, each of which was assessed separately on a 5-point scale, with 1 being the worst and 5 being the best. The obtained indicators were compared with the standards and requirements specified in DSTU 3662:2019 (2019) for milk and cottage cheese. For milk pH, the standard was 6.5-6.8, for acidity – no more than 18°T, the moisture content of cheese – no more than 80%, and the redox potential should not exceed 200 mV to maintain product safety and quality.

The microbiological analysis was carried out using the serial dilution method, which included counting the total number of bacteria and checking for pathogens. Organoleptic tests included the assessment of changes in colour, smell, texture, and taste based on compliance with ISO 4833-1:2013 (2013) for total bacteria and ISO 21528-2:2017 (2017) for enterobacteria. Microbiological studies were carried out using standard methods in accordance with DSTU 4587:2006 (2007). The number of microorganisms in dairy products was determined by incubating samples on agar media, Sabouraud agar for total bacteria and Endo agar for enterobacteria. The incubation conditions consisted of a temperature of 37°C for 24-48 hours for total bacterial colonisation and specific temperatures for specific microorganisms. The number of colonies was counted by counting colony forming units (CFU) per unit volume of the sample.

After completion of the experiment, a comparative analysis of the results was carried out using the statistical method of ANOVA. The variables of pH, acidity, moisture content, redox potential and microbiological parameters were analysed, and statistical analysis was performed by ANOVA with a significance level of $p < 0.05$ using SPSS software.

Results

Current trends in the use of active packaging and nanotechnology for the storage of dairy products

The most common types of packaging for dairy products are plastic bottles, carton bags and glass jars. According to market research conducted by Global Market Insight (2025), the breakdown of packaging materials used for dairy products is as follows: plastic bottles 45%, carton bags 35%, glass jars 15%, and other packaging 5% (Tetra Pak, n.d.). These data show that plastic bottles and carton bags are the most popular packaging options for dairy products, accounting for 80% of the market together. Glass jars and other types of packaging are used much less frequently.

Other types of packaging, such as active antioxidant packaging, silver nanoparticle packaging and cartons with barrier materials, are selected for the study because such packages are effective in helping to preserve the freshness of dairy products. Active packaging with antioxidants works by preventing oxidation, which is the main cause of taste loss in milk and dairy products. The antioxidants in the packaging materials absorb oxygen, thereby reducing the risk of rancidity and keeping the product fresh for a long time (Volpe *et al*., 2022). Packaging with silver nanoparticles provides products with additional protection against microbiological contamination due to its antimicrobial properties, which ensures the preservation of products and prevents spoilage. In addition, cardboard packaging with barrier materials protects products from the negative effects of oxygen, moisture and light, which contributes to the long-term preservation of organoleptic properties. These types of packaging not only provide dairy products with a longer shelf life, but also preserve taste and nutritional qualities, which is important to meet consumer demands for dairy products.

Active antioxidant packaging, silver nanoparticle packaging and carton packaging with barrier materials used for dairy products comply with European regulations such as Regulation (EC) No. 1935/2004 (2004) and Regulation (EU) No. 1169/2011 (2011), ensuring food safety, and the fact that the materials do not emit harmful substances in quantities hazardous to human health and do not cause unacceptable changes in the composition of the products. In addition, these types of packaging are labelled to indicate the presence of nanomaterials, which meets the requirements for clear information on the use of nanomaterials in packaging. For example, active antioxidant packaging used to preserve dairy products contains vitamin E or polyphenols that absorb oxygen and prevent oxidation, which helps to preserve the taste and extend the shelf life of milk and yoghurt. Some European countries use packaging materials for milk and yoghurt that include antioxidants to prevent rancid odours and keep products fresh for a longer time (Bińkowska *et al*., 2024).

Packaging with silver nanoparticles is used for dairy products such as milk and cheeses due to pronounced antimicrobial properties. Silver nanoparticles are able to kill bacteria that can cause dairy products to spoil, which significantly extends shelf life. One of the well-known companies, Nestlé, uses packaging with silver nanoparticles to ensure the freshness and safety of dairy products, reducing the need for additional preservatives (Nestlé, n.d.). Carton packs with barrier materials, such as those used by Tetra Pak (n.d.), effectively protect dairy products from the negative effects of oxygen, water vapour and light. This packaging is optimal for storing milk, yoghurts, and dairy desserts without the need for refrigeration at all stages of distribution. This type of packaging ensures that products remain fresh for a long time and meets the safety and quality standards required by European regulations. Table 1 provides a comparative analysis of the main characteristics of different types of packaging for dairy products, including the impact on freshness, taste and antimicrobial properties.

Table 1. *Comparative analysis of dairy product packaging types and main characteristics*

Packaging type	Main characteristics	Types of dairy products
Active packaging with antioxidants	Packaging with antioxidants helps preserve the freshness of products by preventing oxidation and loss of flavour	Milk, yoghurts, cheeses, sour cream
Packaging with silver nanoparticles	Packaging with silver nanoparticles has antimicrobial properties, which reduces the number of bacteria and extends the shelf life of products	Milk, yoghurts, creams, cheeses
Cardboard packaging with barrier materials	Cardboard packaging with an internal barrier layer is used to prevent exposure to oxygen and preserve the taste characteristics of the product	Milk, liquid yoghurts, milk-based desserts

Source: compiled by the authors

Other promising nanomaterials used in dairy packaging include metal oxides, such as ZnO and TiO_2. These compounds are known for photocatalytic properties, which allow effectively destroying bacteria under the influence of light. In addition, the mentioned compounds provide protection against ultraviolet radiation, which helps to preserve vitamins and biologically active substances in foods. Metal oxides can also improve the mechanical and barrier properties of packaging materials by reducing gas permeability, which extends the shelf life of products. A separate category of nanomaterials in packaging is polymer nanofilms, which create an effective barrier to gases and moisture, reducing product oxidation and loss of quality (Li *et al.*, 2023). Due to the use of nanoparticles in polymers, such films can have additional functional properties, such as antimicrobial activity or the ability to control the release of beneficial compounds. The use of such nanofilms in the dairy industry helps to preserve the organoleptic characteristics of products and prevents changes in texture, taste, and smell throughout the shelf life. The food industry traditionally uses glass, polyethylene and laminated packaging for dairy products. Each of these types of packaging has its own advantages and disadvantages that affect shelf life, product quality and environmental aspects. Table 2 shows the three types of packaging used for dairy products.

Table 2. *Comparative analysis of packaging types for dairy products, including chemical and physical properties*

Characteristic	Active packaging with antioxidants	Packaging with silver nanoparticles	Cardboard packaging with barrier materials
Type of antioxidants	Vitamin E, polyphenols	Silver nanoparticles	None
Mechanism of action	Absorbing oxygen, preventing oxidation	Antimicrobial effect, destruction of bacteria and microorganisms	Barrier to oxygen, water vapour and light
Reducing oxygen levels in packaging	Up to 90% (depending on antioxidants and packaging material)	Up to 85% (reduces bacterial contamination due to reduced oxygen)	Up to 70% (limitation of oxygen penetration through barrier layers)
Shelf life	Extends by 30-50% compared to conventional packaging	Extends by 20-40%, reduces the risk of developing pathogenic microorganisms	Lengthens by 20-30%, protects from light and oxygen
Packaging materials	Polymers containing antioxidants	Polymers with silver nanoparticles, nanocomposites	Cardboard, combined barrier polymer materials

Table 2. Continued

Characteristic	Active packaging with antioxidants	Packaging with silver nanoparticles	Cardboard packaging with barrier materials
Application	Milk, yoghurt, cheese	Milk, cheese, yoghurts, cheeses with added bacterial cultures	Milk, yoghurts, dairy desserts, liquid yogurts
Compliance with European regulations	Regulations (EC) No. 1935/2004 and No. 1169/2011, clear labelling of antioxidants and impact on product composition	Regulations (EC) No. 1935/2004 and No. 1169/2011, "nano" labelling when using nanomaterials	Regulation (EC) No. 1935/2004 on the safety of materials in contact with food
Main advantage	Prolonging freshness, preventing rancid odour	Reducing bacterial contamination, extending shelf life	Protection from oxygen, water and light, long-term storage

Source: compiled by the authors

Table 2 compares the main physical and chemical characteristics of the three types of packaging for dairy products, focusing on properties, effectiveness, use, and compliance with European regulations. Glass packaging is considered one of the best options for storing dairy products, as it does not chemically interact with the product, provides a good barrier against external influences and preserves the taste characteristics (Gadaieva *et al.*, 2024). However, its main disadvantage is its high weight, fragility, and difficulty of transportation. In addition, although glass can be recycled many times, its production process is energy-intensive. Plastic packaging is the most common type of packaging due to its low cost, lightness and convenience, providing an adequate level of protection for products, but are not completely impermeable to oxygen, which can contribute to oxidation processes and shorten the shelf life. In addition, polyethylene is poorly biodegradable, which puts a significant strain on the environment. Laminated packaging, such as cardboard boxes with an inner layer of aluminium or polyethylene (e.g., Tetra Pak), combine the advantages of different materials to provide airtightness, protection from light and oxygen, and a relatively long shelf life. However, the complexity of the structure makes materials difficult to recycle, as different layers of materials need to be separated. However, despite its many advantages, active packaging also has some disadvantages. It is more expensive to produce compared to standard packaging materials, which can affect the final cost of the product for consumers. The use of nanomaterials in packaging requires further research into long-term impact on human health, as some aspects of the interaction with food remain poorly understood. In addition, due to complex chemical composition, nanomaterials may pose additional challenges in terms of environmental disposal. From an environmental point of view, active packaging, despite its effectiveness, raises certain questions (Rechun & Peredriy, 2021). On the one hand, reducing food spoilage and extending its shelf life helps reduce food waste. On the other hand, especially if containing nanomaterials or multilayer components.

Research on the effectiveness of different types of packaging for preserving the quality of dairy products

To assess the attitude of food industry experts to the introduction of active packaging and nanocoatings in dairy production, a survey was conducted, the results of which are presented in Table 3.

Table 3. *Results of an expert survey on the use of active packaging and nanocoatings*

Question	Number of people
Are you familiar with active packaging and nanocoating technologies?	Yes – 34, No – 16
Do you think these technologies can improve the safety of dairy products?	Yes – 38, No – 5, Hard to answer – 7
How do you assess the potential impact of nanocoatings on the quality of dairy products?	Positive – 33, Neutral – 13, Negative – 5
Do you think that using active packaging can reduce product loss due to spoilage?	Yes – 40, No – 4, Hard to answer – 6
What factors are most important to you when choosing dairy products?	Shelf life – 23, Composition – 15, Price – 10, Brand – 2
Are you willing to pay more for dairy products with an extended shelf life?	Yes – 28, No – 15, Hard to answer – 7
What is the acceptable price difference you consider acceptable for such products?	Up to 5% – 20, 5-10% – 18, More than 10% – 5, Not willing to pay more – 7
Do you have any reservations about the use of nanotechnology in the food industry?	Yes – 25, No – 18, Hard to answer – 7
What are the main risks you see in the use of nanomaterials in food products?	Insufficient research – 20, Possible health effects – 18, Lack of regulation – 12
Do you trust scientific studies that confirm the safety of nanocoatings?	Yes – 30, No – 10, Hard to answer – 10
What benefits of active packaging are most significant to you?	Shelf-life extension – 25, Protection against microorganisms – 18, Improving product quality – 7
Can these technologies help reduce food waste?	Yes – 35, No – 8, Hard to answer – 7
Do you support government regulation of the use of nanotechnology in the food industry?	Yes – 43, No – 2, Hard to answer – 5
Are you interested in learning more about these technologies?	Yes – 33, No – 10, Hard to answer – 7
How, in your opinion, can consumer confidence in products with nanocoatings be increased?	Conducting additional research – 23, Informing consumers – 20, Product certification – 7

Source: compiled by the authors

In the study, the control group (standard packaging) showed the fastest negative changes in organoleptic and microbiological characteristics. On the 10th day of storage, an increase in titratable acidity to 20°T was observed in milk, and the pH decreased to 6.2, indicating the development of lactic acid bacteria. On the 12th day, the cottage cheese showed a deterioration in consistency and the appearance of a foreign odour, indicating the onset of spoilage. The second group (active packaging) significantly slowed down oxidative processes and the growth of microorganisms. The acidity of the milk on the 15th day of storage did not exceed 18°T, and the pH remained within 6.4-6.6.

The results of organoleptic tests showed that dairy products stored in nanocoatings retained freshness longer and had stable sensory characteristics. In particular, after two weeks of storage, 80% of the samples with active packaging met high organoleptic standards, while in traditional packaging this figure was only 50%. The organoleptic characteristics remained satisfactory, and changes in the consistency of the cottage cheese began to appear only after 14 days. During the first two weeks of storage, milk, and cottage cheese retained original characteristics without significant changes. The colour remained uniform, with no signs of yellowing or darkening, which could indicate oxidative processes. The smell remained fresh, without any off-flavours, indicating the absence of active microbial development or fat oxidation.

The consistency of the milk remained stable, without sedimentation or stratification. In the case of cottage cheese, the structure of the product remained uniform until the 14th day of storage, with no signs of excessive moisture or lumps. Only after this period did the experts begin to notice slight changes in the texture, including the appearance of a more pronounced whey release, which is typical of the natural ageing process of fermented dairy products. The taste characteristics remained satisfactory throughout the entire period: in the control group, the products began to lose freshness on day 10-12, while the active packaging and nanocoated samples showed longer taste stability. In the active packaging group, there was no rancid taste, which confirmed the effectiveness of antioxidants in preventing fat oxidation. The nanofilm samples inhibited the development of undesirable microflora, which contributed to the preservation of a pure fermented milk taste.

The third group (nanofilm with silver or metal oxide nanoparticles) provided the best level of product quality preservation. The content of microorganisms in the milk was the lowest among all groups, the acidity did not exceed 17°T, and the pH remained stable (6.5-6.7). Sour milk curd retained its characteristics until the end of the experimental period, without significant changes in consistency and smell.

Table 4. *Characteristics of the effectiveness of different types of packaging for dairy products*

Indicator	Control group	Active packaging	Nanofilm
Milk acidity (°T)	20±0.5	18±0.4	17±0.3
pH of milk	6.2±0.1	6.4±0.1	6.6±0.1
Microorganism content (CFU), *Salmonella*, *Listeria monocytogenes*, *Escherichia coli*, *Staphylococcus aureus*, *Bacillus cereus* and *Campylobacter jejuni*	2.5×10^6	1.2×10^6	5.0×10^5
Cheese consistency retention (days)	12	14	15
Taste rating (1-5)	3.5	4.0	4.5
Odour rating (1-5)	3.0	4.0	4.5
Consistency rating (1-5)	3.0	4.0	4.5
Colour rating (1-5)	3.5	4.5	5.0
Overall organoleptic assessment	3.2±0.3	4.0±0.2	4.7±0.1

Source: compiled by the authors based on ANOVA analysis

The statistical analysis showed significant differences between the groups ($p < 0.05$), which confirms the effectiveness of active packaging and nanofilm in extending the shelf life of dairy products.

One of the key indicators that determines the quality of dairy products is the pH level. During storage, it changes due to the development of microorganisms and enzymatic reactions. In control samples stored in conventional packaging, the pH decreased faster, indicating active acid accumulation processes, especially in fermented dairy products. The active packaging with antimicrobial and antioxidant properties helped to maintain a more stable pH level throughout the storage period. Acidity is another important parameter. It increases due to the metabolic activity of bacteria. In products packaged in standard materials, this process was faster, while active packaging and nanocoatings significantly slowed down the formation of excess acidity, while maintaining optimal conditions for consumption. The moisture content of a product affects its texture and microbiological stability. In dairy products with a high moisture content, such as cheese or yoghurt, improper packaging can lead to excessive drying or, conversely, condensation, which promotes microbial growth. Polymeric nanofilms with barrier properties

helped control the moisture level, preventing its loss or oversaturation. Another important indicator is the ORP. High values of the ORP promote the oxidation of fats, which can lead to the development of a rancid taste and deterioration of product quality. Antioxidant active packaging slowed down these processes, which had a positive impact on the preservation of the taste and smell of dairy products. The results of moisture and redox potential measurements for dairy products stored in different types of packaging are shown in Table 5.

Table 5. *Results of moisture and ORP measurements for dairy products with different types of packaging*

Packaging type	Humidity, %	Oxidation reduction potential (ORP), mV
Standard packaging	87 ± 0.5	200 ± 5
Active packaging	85 ± 0.4	180 ± 4
Packaging with silver nanoparticles	84 ± 0.3	170 ± 3

Source: compiled by the authors

The results of the moisture and ORP measurements showed that the active packaging and silver nanoparticle packaging contributed to a reduction in moisture and an improvement in redox potential compared to the standard packaging.

One of the main functions of active packaging and nanocoatings is to prevent bacterial growth. The study found that in control samples of dairy products, the number of bacteria, in particular the gram-negative bacteria *Escherichia coli* and *Pseudomonas* spp. increased sharply on the 3-5th day of storage. This is due to the lack of additional barriers in standard packaging, which contributed to the active reproduction of microorganisms due to the lack of antimicrobial properties. The use of nanocoatings with silver particles or metal oxides, such as ZnO and TiO_2, has led to a significant reduction in the number of microorganisms in dairy products, including a 50-60% reduction in bacterial contamination. This resulted in an extended shelf life and improved organoleptic properties of the products. As a result, the products in this packaging remained safe for consumption for 5-7 days longer compared to the control samples. In addition to the overall reduction in bacterial contamination, active packaging also reduced the risk of pathogenic microorganisms such as *Salmonella*, *Listeria monocytogenes* and *Escherichia coli*. The level of reduction of bacterial contamination for pathogens such as *Salmonella*, *Listeria monocytogenes* and *Escherichia coli* was 40-60%, which indicates the effectiveness of such packaging in ensuring product safety.

The results demonstrated that the dairy samples packaged with nanocoatings contained significantly fewer bacteria compared to traditional packaging materials. Changes in the organoleptic characteristics of samples stored in conventional packaging were faster, and already on the 5th-6th day of storage, signs of a rancid smell were observed, and the texture changed (dryness or excessive moisture). The active packaging containing antioxidant components helped to preserve the natural taste and smell of the products, as it prevented the oxidation of fats, as determined by experts.

Discussion

The results confirmed the effectiveness of active packaging and nanocoatings in preserving the quality of dairy products, reducing microbial contamination and extending shelf life. Similar conclusions are contained in the works of A. Mirza Alizadeh *et al.* (2022), who reviewed trends in the use of smart packaging for dairy

products. The study showed that such materials can prevent product spoilage by actively controlling the environment. L. Bandera (2025) studied the impact of various packaging materials on food safety and confirmed that active packaging helps to reduce the level of contamination with pathogens, which is consistent with the results obtained. Similar conclusions were made by I. Barukčić *et al.* (2021), who found that the use of packaging technologies reduces the effects of oxygen and moisture on dairy products, helping to preserve organoleptic properties.

The use of nanostructured antimicrobial agents in packaging was analysed in study A. Brandelli *et al.* (2023). In the work, the authors investigated the effectiveness of various types of nanomaterials, in particular silver and zinc nanoparticles, in the fight against pathogens commonly found in dairy products. It has been found that the use of such nanocomponents in active packaging contributes to a significant reduction in the number of *Escherichia coli*, *Listeria monocytogenes* and *Staphylococcus aureus bacteria*, which, in turn, extends the shelf life of products and improves the microbiological stability. In addition, the authors emphasise the importance of controlling the safety of nanomaterials, as the migration into food remains a pressing issue. Similar results were obtained by Y. Li *et al.* (2023), who studied the effect of bactericidal components, including chitosan, metal nanoxides, and bioactive polymers, on milk quality. The study confirmed that active packaging with built-in antimicrobial agents significantly slows down the growth of microorganisms in raw and pasteurised milk, reducing the rate of fat oxidation and preventing the formation of undesirable metabolites. An important aspect of the work was the comparison of the effectiveness of traditional preservatives and the latest nanostructured agents: the results showed that nanomaterials provide longer protection without affecting the taste and texture of dairy products. A separate area of research concerns edible coatings as an alternative approach to active packaging. S. El-Sayed & A. Youssef (2024) studied the use of edible biopolymer coatings for cheese packaging, in particular coatings based on alginate, carboxymethyl cellulose, and gelatin. It was found that such coatings effectively reduce moisture loss, prevent fat oxidation and slow down the growth of spoilage microorganisms, which helps to preserve the texture and taste of the product. The results confirm that nanocoatings have a significant potential for maintaining the stability of the chemical composition of dairy products and can become an environmentally friendly alternative to traditional packaging. The use of a modified gas environment (MGE) in combination with active packaging is one of the most effective methods of extending the shelf life of dairy products (Shebanina *et al.*, 2024). The study by R. Chawla *et al*. (2021) confirmed that the use of gas mixtures with controlled oxygen, carbon dioxide and nitrogen content together with antimicrobial coatings helps to reduce the growth of pathogens, which has a positive impact on the quality and safety of dairy products. The effect of packaging materials on the structure and consistency of dairy products was studied by S. Harmankaya *et al.* (2022), who investigated the stability of yoghurt. It was found that active packaging components prevent product stratification while maintaining its texture and sensory characteristics. In addition to these studies, D. Francis *et al.* (2024) proved that biodegradable active materials not only extend the shelf life of fermented dairy products, but also preserve the nutritional properties. This opens up prospects for the widespread adoption of eco-friendly packaging technologies in the dairy industry.

The study by M. Vasuki *et al.* (2023) confirmed the effectiveness of smart packaging, which ensures continuous monitoring of the condition of dairy products during storage and transportation. The authors analysed the use of freshness indicators that change colour depending on the pH, temperature or gas

concentration in the packaging. This allows for timely detection of product spoilage and significantly reduces the amount of food waste, as the consumer receives accurate information about its suitability for consumption. The study also showed that the integration of nanosensors into packaging materials can significantly improve food safety, as it is possible to detect microbial contamination at an early stage. The findings are in line with a study that confirmed the effectiveness of active packaging technologies in maintaining consistent quality of dairy products. The combination of smart indicators with nanocoatings helps to extend shelf life and minimise the risks associated with bacterial contamination. In addition to classic packaging materials, edible coatings are a promising area. A study by M. Mikus & S. Galus (2025) focused on the use of biopolymer films for fruit, but the authors noted that similar technologies could be adapted for dairy products. In particular, edible coatings based on gelatin, starch, alginate, and chitosan can create a barrier to oxygen and moisture, which prevents dairy products from spoiling (Remizova *et al.*, 2024). In addition, such coatings can be enriched with antioxidants and antimicrobial agents, which will further protect the products. The results of this study correlate with the data obtained on the positive impact of nanocoatings on the stability of the chemical composition of dairy products. The use of such technologies can become an environmentally friendly alternative to traditional plastic packaging and contribute to the development of sustainable food production.

Despite the numerous advantages of nanopackaging, its widespread use requires compliance with international food safety standards. A study by Y. Burylo *et al.* (2023) focused on the regulatory framework for packaging materials in the EU and Ukraine. The authors found that the use of nanoparticles in the food industry does not yet have a clear legal framework, and some countries require additional research on the safety of such materials for consumers. In particular, the EU has Regulation (EC) No. 1935/2004 regulating materials in contact with food, but certain aspects of nanotechnology in packaging need to be clarified (Semenenko *et al.*, 2021; Dankevych *et al.*, 2024). In Ukraine, the legal framework is still evolving, which creates additional challenges for manufacturers seeking to use innovative packaging solutions. Thus, the introduction of nanopackaging in the food industry should be accompanied by the development of appropriate standards and research to confirm its safety for human health. In the work, D. Nath *et al.* (2022) considered the possibilities of using nanocomposite materials in food packaging and found that such materials can significantly improve the mechanical and barrier properties of packaging materials. Similar results were obtained in the works of M. Gogliettino *et al.* (2020), T. Niaz *et al.* (2022), and C. Figueroa-Enríquez *et al*. (2024), where the effectiveness of nanoparticles for preserving the freshness of dairy products was demonstrated. A. Karnwal *et al.* (2025) emphasised the importance of using natural biopolymers in food packaging, stressing that such materials can provide additional protection of dairy products from the negative effects of the environment. Vandana & K. Sinha (2019) conducted a general analysis of the impact of packaging on the shelf life of milk and dairy products, noting that the effectiveness of packaging technologies largely depends on storage conditions and the interaction of the packaging material with the product. The results confirmed the effectiveness of active packaging and nanocoatings in maintaining the safety, quality, and shelf life of dairy products.

In the US, the use of nanomaterials in food and packaging is regulated by the Food and Drug Administration (FDA) (Kudrenko & Hall, 2024). The FDA requires manufacturers to conduct a safety assessment of nanomaterials before being introduced to the market. In particular, if a nanomaterial is used as a food additive or food contact material, it must meet safety

requirements and be approved for use (Export to the USA..., 2025). The World Health Organisation (WHO), together with the Food and Agriculture Organisation (FAO), develops standards and recommendations for food safety, including the use of nanotechnology. The Codex Alimentarius standards are aimed at guaranteeing the consumer a safe food product that is free from falsification, properly labelled and meets established quality standards (Uzenbaev *et al.*, 2019).

The main restrictions and requirements for the use of nanomaterials in the food industry include the fact that before introducing nanomaterials into food or packaging, a thorough assessment of the safety for human health must be carried out. This includes toxicity studies, the potential for nanoparticles to migrate from the packaging into the product, and an assessment of the effects on the body upon consumption. In the EU, the presence of nanomaterials in food products must be clearly indicated in the ingredient list with the "nano" mark next to the name of the respective ingredient. This provides transparency for consumers and enables consumers to make informed choices. Governments and international organisations are constantly monitoring the use of nanotechnology in the food industry. This includes monitoring new research on the safety of nanomaterials, updating regulations and introducing new standards where necessary. Thus, the use of nanotechnology in the food industry is regulated by a number of international and national regulations aimed at ensuring consumer safety. Manufacturers planning to introduce nanomaterials into products or packaging must strictly comply with the established requirements, conduct the necessary research and ensure transparent information to consumers about the presence of nanomaterials in the products.

Conclusions

It has been found that the use of antimicrobial and antioxidant components in active packaging can effectively inhibit the development of microorganisms and oxidative processes, which has a positive effect on the physicochemical and organoleptic characteristics of products. The study assessed the impact of different types of packaging on the quality and safety of dairy products. The experts confirmed that all types of packaging met the established safety standards, which ensured that the quality of the products was maintained during the storage period. The study found that the use of nanocoated packaging contributed to better preservation of dairy products. Milk and cheese stored in nanocoated packaging had significantly lower bacterial counts than control samples. During the organoleptic test, it was found that the products in the nanocoated packaging retained freshness, colour and smell better than the other samples. In addition, a reduction in oxidation and spoilage processes was recorded in these samples. Statistical analyses showed a significant difference between the samples in the control and experimental groups in terms of quality and microbiological characteristics. In particular, the average number of bacteria in the control milk samples was 8.5×10^4 CFU/ml, while in the samples with nanocoated packaging it was 3.2×10^4 CFU/ml. Similar results were obtained for cottage cheese. Instead, active packaging, especially those with antimicrobial properties, can reduce the rate of product spoilage, extending shelf life by an average of 3-5 days compared to traditional packaging materials. Nanocoatings, in particular those containing silver and metal oxide nanoparticles, demonstrated the highest efficiency. Such nanocoatings helped to maintain a stable level of acidity and moisture in dairy products, as well as reduce bacterial contamination, which allowed for a 5-7-day shelf-life extension. It has been confirmed that active packaging and nanocoatings do not have a negative impact on the taste, smell, and texture of dairy products, provided that the dosage of active ingredients is correct. However, excessive concentration

of nanoparticles can change the sensory characteristics of products, which requires further research to optimise composition. Future research may also focus on the development of biodegradable nanocoatings, as well as on improving methods for monitoring the safety of packaging materials in real-world production and storage conditions.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

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Вплив активної упаковки та нанопокриттів на безпеку та термін придатності молочних продуктів

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Анотація. Метою дослідження було визначення ефективних методів підтримки якості та безпеки молочної продукції шляхом використання активної упаковки та нанотехнологій. Методологія включала аналіз нормативних документів та сучасних тенденцій у технологіях упаковки, а також експериментальні дослідження з використанням контрольної та експериментальної груп. Дослідження показало, що молоко та сир, упаковані у стандартну картонну упаковку з внутрішнім шаром алюмінієвої фольги, показали середній вміст вологи 88,2 ± 0,5 % та окисно-відновний потенціал 185 ± 2 мВ. У групі з активною упаковкою, що містила антиоксидантні компоненти, вміст вологи становив 87,5 ± 0,4 %, а окислювально-відновний потенціал (ОВП) знизився до 175 ± 1 мВ. Найвищу ефективність показала упаковка з наночастинками срібла, де вміст вологи в молоці та сирі становив 86,7 ± 0,3 %, а ОВП досяг 170 ± 1,5 мВ, що свідчило про зниження рівня окислювальних процесів та покращене збереження продукту. Крім того, дослідження показало, що молоко та сир, що зберігалися в активній упаковці та упаковці з наноплівкою, демонстрували значно кращі органолептичні характеристики порівняно з контрольними зразками. Зокрема, смак, запах, текстура та колір отримали вищі бали за шкалою від 1 до 5. Для контрольної групи середня оцінка смаку становила 3,2 ± 0,3, для активної упаковки – 4,0 ± 0,2, а для наноплівки – 4,7 ± 0,1. Подібні результати були зафіксовані для запаху (3,2 ± 0,3, 4,1 ± 0,2 та 4,8 ± 0,1 відповідно), текстури (3,1 ± 0,4, 4,0 ± 0,3 та 4,6 ± 0,2) та кольору (3,0 ± 0,2, 4,2 ± 0,1 та 4,7 ± 0,1). Ці дані свідчили про значне покращення органолептичних характеристик молочних продуктів, що зберігалися в активній упаковці та упаковці з наноплівкою, порівняно з контрольними зразками. Практичне значення дослідження полягало в розробці рекомендацій для виробників молочної продукції щодо вибору пакувальних матеріалів залежно від строку придатності та умов продажу. Отримані результати можуть бути використані в харчовій промисловості для впровадження інноваційних технологій упаковки, а також слугувати основою для подальших досліджень у галузі безпеки харчових продуктів та розробки екологічно чистих пакувальних матеріалів

Ключові слова: інноваційні технології; промислова якість; наноматеріали; антиоксиданти; антимікробні властивості

ANIMAL SCIENCE AND FOOD TECHNOLOGY

Journal homepage: https://animalscience.com.ua/en
Animal Science and Food Technology, 16(2), 129-147
Received 02.02.2025 Revised 23.04.2025 Accepted 22.05.2025

UDC 664.8:631.15
DOI: 10.31548/animal.2.2025.129

Evaluation of technological parameters in the production of beverages based on fermented plant ingredients

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Abstract. The aim of the study was to determine the optimal conditions for the fermentation of plant raw materials to ensure the stability and a favourable combination of sensory, microbiological, and physicochemical properties in beverages. The research was conducted under laboratory conditions and involved the fermentation of beverages from plant-based ingredients using both traditional and combined technologies. Physicochemical (pH, titratable acidity, redox potential), microbiological (counts of lactic acid bacteria and yeasts), and sensory parameters

Suggested Citation:
Petrova, O., Shevchuk, N., Trybrat, R., & Bolodurin, V. (2025). Evaluation of technological parameters in the production of beverages based on fermented plant ingredients. *Animal Science and Food Technology*, 16(2), 129-147. doi: 10.31548/animal.2.2025.129.

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were monitored. It was found that combined fermentation resulted in a more rapid reduction in beverage pH (down to 4.0 within 72 hours) compared to traditional lactic acid fermentation (pH 4.6). The lowest pH (3.8) and highest titratable acidity (8.5 g/L) were observed in beverages based on fruit extracts, contributing to enhanced microbiological stability. Kombucha-based beverages exhibited intermediate acidity (6.5 g/L), while those produced from cereal substrates had the lowest acidity (5.7-6.0 g/L) and the shortest shelf life (10-12 days). Sensory analysis confirmed the advantages of combined fermentation: beverages produced using this method achieved a more complex aromatic profile and balanced taste, scoring 8.3 on a nine-point scale. Microbiological analysis revealed that yeast populations peaked at 48 hours (7.8 log CFU/mL) before declining, whereas lactic acid bacteria continued to increase until the end of fermentation (7.5-7.1 log CFU/mL). Correlation analysis confirmed the influence of acidity on both microbial composition and sensory characteristics. The results demonstrated that combined fermentation leads to a more significant pH reduction, increased titratable acidity, and stabilisation of redox potential, thereby improving the microbiological stability and sensory quality of beverages. This approach enables the optimisation of functional fermented beverage production, enhancing organoleptic properties and extending shelf life

Keywords: fermentation; acidity; redox potential; lactic acid bacteria; yeast; sensory analysis; microbiological stability

Introduction

Fermented beverages based on plant-derived raw materials are gaining increasing popularity due to their functional properties, high nutritional value, and potential health benefits. The fermentation process enhances the bioavailability of nutrients, reduces the content of anti-nutritional compounds, and contributes to the development of a distinctive sensory profile. In particular, lactic acid and yeast fermentation promote the synthesis of bioactive compounds – such as organic acids, poalyphenols, and B vitamins – which increase the antioxidant activity and probiotic potential of the beverages. However, the efficiency of the fermentation process largely depends on the selection of microbial cultures, fermentation parameters, and the type of plant raw material used (Dudarev, 2024). These factors underline the importance of optimising technological regimes to produce a high-quality and stable final product. Despite growing interest in plant-based fermented beverages, the control of physicochemical parameters during production, as well as the influence of different microbial strains on beverage quality, remains insufficiently studied.

Globally, the development of innovative fermentation methods for plant-based beverages is recognised as a priority area within the broader strategies for healthy diets and food security (Bekbayev *et al.*, 2024). The World Health Organization (n.d.) and the Food and Agriculture Organization (n.d.) highlight the role of fermented foods in enhancing the nutritional quality of diets and reducing the risk of chronic diseases (Ismayilov *et al.*, 2023). Numerous studies have examined the impact of technological parameters on the physicochemical properties, microbiological stability, and organoleptic characteristics of fermented plant-based beverages. Research has focused on modern processing methods, safety control, and fermentation optimisation. For instance, the study by M. Karputina & S. Oliinyk (2024) demonstrated that optimising fermentation processes improves the quality and microbiological safety

of low-alcohol plant-based beverages, particularly through the selection of specific microbial strains and adjustment of technological conditions. R. Hrushchetskyi *et al.* (2023) highlighted the potential of Ukrainian plant raw materials – including rare vegetables and fruits – for creating innovative fermented beverages with both high nutritional value and distinctive sensory attributes. The study by K. Kondratenko (2023) focused on the development of fermented beverage technologies from vegetable substrates, showing that fermentation time and the choice of starter culture significantly influence acidity, stability, and consumer acceptance of the final product. Meanwhile, C. Penha *et al.* (2021) investigated the use of environmentally friendly technologies in producing plant-based beverages, particularly fermentation using probiotic cultures, which contributed to preserving sensory qualities and enhancing nutritional value.

Considerable attention has been devoted to enhancing the functional properties of fermented beverages through the optimisation of fermentation processes and the incorporation of additional bioactive components. A. Keșa *et al.* (2021) investigated strategies to improve the biological activity of fruit-based beverages by employing probiotic cultures and regulating fermentation parameters. Similarly, S. Liang *et al.* (2021) analysed technological processes in the production of tea-based beverages, focusing on the integration of traditional and innovative methods to enhance both sensory and chemical characteristics. L. Zhang *et al.* (2021) reviewed recent technological advancements aimed at eliminating defects in the production of fermented plant products, particularly the use of alternative fermentation methods to preserve nutritional value. Significant emphasis on biotechnological approaches to the production of fermented beverages from non-traditional plant raw materials was evident in the study by A. Vavilova (2023), which underscored the influence of microorganism type and technological conditions on the stability, chemical composition, and sensory acceptability of the final product. O. Kovalova *et al.* (2024a) note that "the use of plasma-chemically activated aqueous solutions increases the efficiency of enzymatic processing of lentils, improves the quality of the malted product, and promotes the activation of biochemical processes important for the production of functional beverages". In a related study, O. Kovalova *et al.* (2024b) emphasise that "the use of plasma-chemically activated water in the production of oat malt allows for the achievement of stable acidity indicators and the optimisation of enzymatic activity in the substrate, which is a prerequisite for high-quality fermentation". I. Ivanova *et al.* (2024) demonstrate that "the use of ridge regression to predict acidity and dry matter content in fruits enables the effective selection of raw materials with suitable fermentation characteristics – an essential factor in ensuring beverage stability and flavour".

Despite advances in research, the relationships between fermentation parameters, microbiological changes, and organoleptic characteristics – as well as the effects of different combinations of microorganisms on beverage stability and functional properties – remain insufficiently explored. The aim of this study was to evaluate the technological parameters of fermentation and their impact on the quality of beverages derived from plant-based raw materials. The specific objectives were to determine the influence of enzymatic agents and fermentation parameters on acidity, redox potential, and organoleptic characteristics; to analyse microbiological changes and their correlation with the physicochemical properties of the product; and to assess beverage stability depending on the choice of raw materials and fermentation conditions.

Materials and Methods

The experimental work was conducted from April to November 2024 at the Department of Food Biotechnology and the Laboratory of

Microbiological Quality Control of the National University of Food Technologies (NUFT) in Kyiv, Ukraine. Physicochemical analyses – including the determination of redox potential, acidity, and sugar content – were performed at the Central Research Laboratory of NUFT using certified equipment in accordance with Good Laboratory Practice (GLP) standards (European Food Safety Authority, n.d.). Seven groups of plant-based raw materials, differing in biochemical composition, were selected for fermentation: oats, millet, and barley (cereals); pomegranate, apple, and citrus extracts (fruits); and kombucha infusion (tea mushroom). Oat grain of the Harmony variety (Limited Liability Company "Agroprom-Lan", Kyiv region) was cleaned, washed, dried, crushed to a particle size of 0.8-1.2 mm, and extracted at 95°C for 30 minutes. Millet (Yavir) and barley (Karat) underwent the same treatment. The prepared substrates were used at a concentration of 500 g per 3 litres of medium.

Pomegranates of the Crimean Ruby variety (Kherson region) were processed by cold pressing, followed by settling and concentration to 16% dry matter. The resulting concentrate was added at a dose of 300 ml per 3 litres. Apple extract was obtained from the Golden Delicious variety through juice pasteurisation and clarification. The citrus blend – comprising Meyer lemons and Washington Navel oranges (Turkey, Fruit Line LLC) – was blanched, crushed, pasteurised, and added at a concentration of 150 g per 3 litres. Kombucha infusion (*Medusomyces gisevii*) from the laboratory collection was activated in a 5% black tea infusion at 28°C for 7 days. Following activation, the biofilm was rinsed with sterile 0.9% NaCl solution and added to the fermentation medium at a ratio of 1:5. All cereal-based samples and the Kombucha infusion were fermented using the traditional lactic acid fermentation method, while fruit extracts were subjected to a combined fermentation scheme, beginning with an initial yeast phase. This division was based on the buffer capacities of the raw materials and their suitability for supporting the growth of specific microorganisms.

All experiments were conducted using pure cultures of *Lactobacillus plantarum, Lactobacillus casei, Saccharomyces cerevisiae*, and *Brettanomyces bruxellensis*, obtained from the DSMZ (Germany) and CBS (Netherlands) collections in accordance with ISO 7889:2003 (2003). The microbial cultures were stored in lyophilised form at −18°C and were activated prior to fermentation: bacteria in De Man, Rogosa, and Sharpe (MRS) broth at 37°C for 18 hours, and yeast in a glucose-malt medium at 28°C for 24 hours. Following incubation, the cultures were standardised by concentration and introduced into 3 L of the respective fermentation media. The fermentation process was conducted under conditions tailored to the specific raw material and microbial characteristics, at temperatures ranging from 25 to 37°C. For each of the three primary substrates – oats, pomegranate, and citrus extract – the fermentation volume was 3 L. Inoculation was performed at a concentration of 10^6 colony-forming units (CFU)/mL for lactic acid bacteria and 10^5 CFU/mL for yeast in the case of combined fermentation. Samples were collected at key time points – after 24, 48, 72, 96, and 120 hours – for the analysis of physicochemical parameters, microbial composition, and sensory attributes.

In the series involving traditional lactic acid fermentation, cereal samples and Kombucha infusion were cultivated in 3-litre bioflasks equipped with water locks, creating a partially anaerobic environment. To enhance anaerobiosis, the fermentation medium was pre-degassed with sterile nitrogen for 15 minutes and sealed with silicone stoppers fitted with valves. The fermentation was conducted at a constant temperature of 37°C, with a total duration of up to 120 hours. Fruit extracts underwent combined fermentation. The first (yeast) phase lasted 48 hours at 28°C under aerobic

conditions, facilitated by sterile air supply at a rate of 1.0 L/min into 5-litre bioreactors equipped with adjustable aerators. After this phase, aeration was discontinued, the temperature was increased to 37 °C, and lactic acid bacteria were introduced for the second fermentation stage under anaerobic conditions, which lasted an additional 48-72 hours.

The pH of the samples was measured using a SevenCompact S220 pH meter (Mettler Toledo, Switzerland) with an InLab Expert Pro electrode, calibrated using buffer solutions with pH values of 4.01, 7.00, and 9.21. Redox potential was determined potentiometrically using an InLab Redox Pro platinum electrode (Mettler Toledo, Switzerland), pre-calibrated with a standard redox solution. Measurements were taken every 24 hours to assess the redox environment and microbial activity throughout the fermentation. Titratable acidity was determined using an automatic titrator (HI931, Hanna Instruments, Italy) with 0.1 mol/L sodium hydroxide (NaOH), standardised against potassium hydrogen phthalate. Total sugar content was assessed spectrophotometrically following its reaction with anthranilic acid, enabling a comprehensive evaluation of the fermentation process and product quality. The number of lactic acid bacteria and yeasts was determined by surface plating on selective media: MRS agar (HiMedia, India) incubated at 37°C for 48 hours under anaerobic conditions, and Sabouraud agar (Biolife, Italy) incubated at 28°C for 72 hours under aerobic conditions. Colony counts were conducted following serial dilution, within the range of 30-300 CFU per plate. The stability of the fermented beverages was assessed over a 28-day storage period at 4 ± 1°C in sterile 250 ml glass containers. Observations were conducted every 2 days, with measurements of pH and titratable acidity, and records of visual changes and organoleptic properties. A beverage was considered stable if no sediment, off-odour, or pH variation greater than 0.3 units was detected.

Sensory evaluation was performed using profile analysis on a 9-point scale (1 = minimal perception, 9 = maximal perception) by a panel of 15 trained experts with prior experience in sensory assessment. The study adhered to the ethical principles outlined in the Declaration of Helsinki (1964) regarding research involving human subjects. Attributes such as aroma, clarity, acidity, and aftertaste were evaluated under standardised conditions (22°C, 100 ml samples, randomised order). Data analysis was conducted using SPSS Statistics 26.0 (IBM, USA). One-way analysis of variance (ANOVA) with Tukey's post-hoc test was applied to assess differences between samples ($p < 0.05$). Correlations between physicochemical and sensory parameters were calculated using the Pearson correlation coefficient. The study was conducted in accordance with international standards for food safety and Good Laboratory Practice (GLP), as outlined by the European Food Safety Authority (n.d.). All microorganisms were sourced from reference collections, and analytical procedures complied with ISO 22000:2018 (2018) and Codex Alimentarius (n.d.), ensuring the reliability and reproducibility of results.

Results

Dynamics of changes in physicochemical parameters during fermentation

Traditional lactic acid fermentation (applied to cereal substrates and Kombucha) and combined fermentation (used for fruit extracts) exhibit distinct mechanisms of acid formation and differing dynamics in pH, redox potential, and titratable acidity. At the initial stage, pH values varied according to the type of plant raw material: in samples based on cereal substrates (oats, millet, barley) and Kombucha, the pH averaged 6.0-6.2; whereas in fruit extracts (pomegranate, apple, citrus), it ranged from 4.2 to 5.1. The subsequent dynamics of pH reduction were significantly influenced by both the type of raw material and the fermentation method employed (Fig. 1).

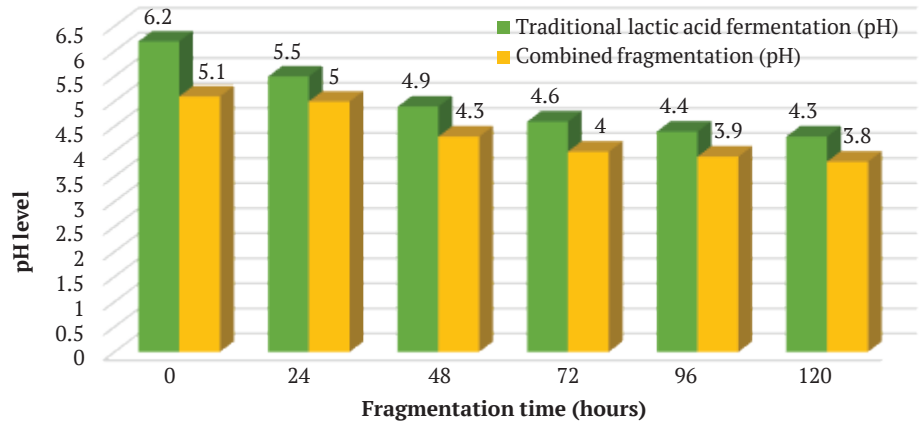

Figure 1. Dynamics of pH changes during fermentation

Source: created by the authors

In traditional fermentation, the average pH value in the experimental samples gradually decreased from an initial 6.2 to 5.5 at 24 hours, 4.9 at 48 hours, and 4.6 at 72 hours. Thereafter, it stabilised within the range of 4.4-4.3 by the end of the process, indicating a steady and uniform production of organic acids. In the samples subjected to combined fermentation, the initial pH was lower (5.1) and decreased more rapidly – reaching 5.0 at 24 hours, 4.3 at 48 hours, and 4.0 at 72 hours. These dynamics, observed across beverages based on different plant substrates – fruit extracts, cereal-based media, and Kombucha infusion – reflect a more active metabolic process during the initial yeast fermentation phase. The redox potential exhibited the following trend: at the early stages of fermentation, an increase in redox values was observed, attributed to the active formation of intermediate metabolites and changes in the gaseous composition of the medium. As fermentation progressed, the redox potential gradually declined, indicating the establishment of a stable anaerobic environment conducive to the growth of lactic acid bacteria (Fig. 2).

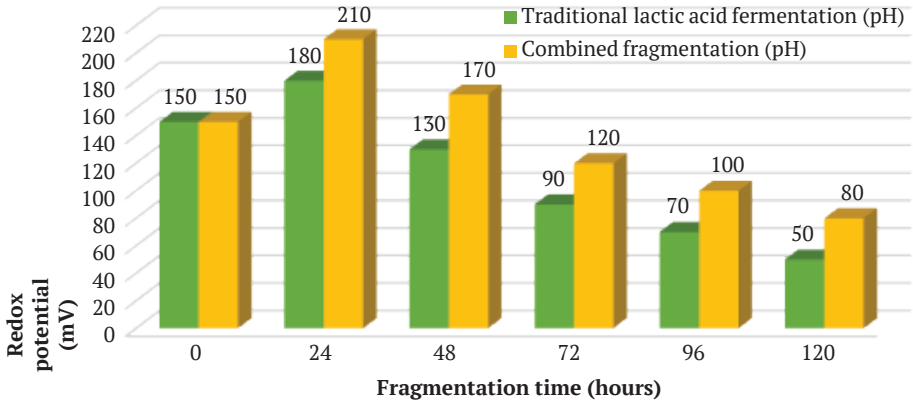

Figure 2. Dynamics of changes in redox potential (mV) during fermentation

Source: created by the authors

In the group undergoing traditional lactic acid fermentation – which included beverages based on cereal substrates (oats, millet, barley) and Kombucha infusion – the initial redox potential (ROP) was measured at 150 mV, indicating a mildly oxidising environment with moderate microbial activity. At 24 hours, the ROP increased to 180 mV, reflecting active oxygen consumption by microorganisms and the formation of oxidised metabolites such as pyruvate and acetaldehyde. Subsequently, as partial anaerobic conditions developed, a steady decline in ROP was observed, reaching 50 mV by 120 hours. This reduction signified the end of the intensive metabolic phase and the onset of the stabilisation stage. In contrast, samples subjected to combined fermentation (i.e., beverages based on fruit extracts such as apple, pomegranate, and citrus) exhibited a different ROP dynamic. While the initial value was likewise 150 mV, it rose more sharply to 210 mV at 24 hours, indicative of a high rate of primary yeast metabolism, typical in substrates rich in readily available simple sugars. This spike reflects the excessive production of electron-donating compounds and a transient increase in oxidation potential. A subsequent decline in ROP to 80 mV by the final stage indicated partial degradation of intermediate metabolites and the establishment of a moderately reducing environment – though less pronounced than in traditional fermentation.

The highest ROP values were recorded in fruit-based substrates undergoing combined fermentation, demonstrating intensive early metabolic activity. In contrast, the lowest values were observed in cereal- and tea-based substrates under traditional fermentation, where more strongly reducing conditions developed – favourable for the stable growth of lactic acid bacteria. The titrated acidity in the experimental samples increased progressively throughout the fermentation process; however, the rate of increase was markedly influenced by the type of raw material and the fermentation method employed. The highest acidity level – up to 3.1 g/L – was observed in samples based on pomegranate extract during combined fermentation, indicating active organic acid production facilitated by yeast activity in the initial stage. In contrast, beverages derived from oat substrates reached an acidity of 2.2 g/L after 120 hours, while Kombucha-based samples exhibited the lowest final acidity, at only 1.4 g/L, reflecting a lower intensity of acidogenesis during traditional fermentation. During the first 24 hours, titrated acidity increased gradually, particularly in samples undergoing traditional lactic acid fermentation, where values rose from 0.2 to 0.5 g/L. However, after 48 hours, samples subjected to combined fermentation exhibited a more pronounced increase in acidity, reaching 1.9 g/L at 72 hours and 3.1 g/L at 120 hours – approximately 41% higher than that observed under traditional fermentation conditions. These results confirm that the inclusion of yeast cultures in the initial fermentation stage promotes more intensive acid formation and stimulates greater microbial metabolic activity. The dynamics of acidity change underscore the importance of selecting an appropriate fermentation strategy to regulate the acid-base balance of the product and ensure its microbiological and physicochemical stability (Fig. 3).

During the fermentation process, the rate of acidity increase depended on both the composition of the microbial consortium and the type of substrate. Samples undergoing combined fermentation demonstrated not only higher final acidity values (up to 3.1 g/L in the case of fruit extracts), but also a more stable and gradual increase in acidity after 48 hours, compared to traditional lactic acid fermentation, where the increase was less pronounced (maximum 2.2 g/L for cereal-based substrates). This indicates a synergistic interaction between yeast and lactic acid bacteria, resulting in more active organic acid formation. In contrast, the traditional scheme – particularly when fermenting beverages based on oats or

Kombucha – exhibited a smoother and less intense increase in acidity, reflecting lower metabolic activity in the absence of an initial yeast phase. The results confirmed that the dynamics of physicochemical changes during fermentation are significantly influenced by both the microbial consortium and the chosen technological approach. Combined fermentation led to a more intensive increase in titrated acidity and a more rapid decrease in redox potential, indicating more active organic acid formation and the establishment of a stable anaerobic environment. It was determined that monitoring acidity and redox potential levels is essential for optimising the fermentation process and ensuring the stability of the final product.

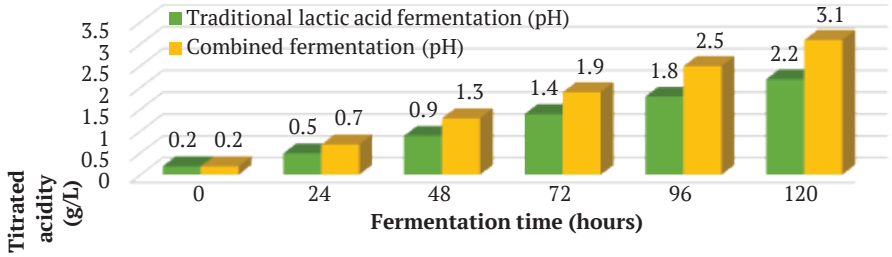

Figure 3. Dynamics of changes in titrated acidity during fermentation
Source: created by the authors

Microbiological changes during the fermentation process

During the fermentation of plant-based beverages produced from various raw materials – including cereal substrates (oats, millet, barley), fruit extracts (pomegranate, apple, citrus), and kombucha infusion – significant changes were observed in the populations of lactic acid bacteria and yeasts, which directly influenced the quality of the final product. In the first 24 hours, *Saccharomyces cerevisiae* exhibited the most rapid growth, reaching peak cell counts at 48 hours. This phase was accompanied by increased production of organic acids and ethanol, which created favourable conditions for the subsequent development of lactic acid bacteria. Following this, an intensive increase in the populations of *Lactobacillus plantarum* and *Lactobacillus casei* was recorded, contributing to a further reduction in pH and stabilisation of the fermentation process. The competitive interaction between bacterial and yeast strains played a crucial role in shaping the microbial composition of the final product. By 72 hours, the concentration of *S. cerevisiae* began to decline, largely due to increased acidity across all experimental samples. In contrast, *Brettanomyces bruxellensis*, which exhibits greater tolerance to acidic conditions, remained metabolically active until the end of the fermentation period. However, its population levels were consistently lower than those of *S. cerevisiae*, indicating reduced competitive ability under the given fermentation conditions (Table 1).

Table 1. *Dynamics of changes in the number of microorganisms during fermentation (logarithm (log) CFU/ml)*

Time (hours)	*Saccharomyces cerevisiae*	*Brettanomyces bruxellensis*	*Lactobacillus plantarum*	*Lactobacillus casei*
0	3.2	2.8	3.0	3.1
24	6.5	3.2	4.2	4.0
48	7.8	4.0	5.8	5.5
72	6.9	4.2	6.8	6.5

Table 1. Continued

Time (hours)	*Saccharomyces cerevisiae*	*Brettanomyces bruxellensis*	*Lactobacillus plantarum*	*Lactobacillus casei*
96	5.2	4.1	7.2	6.9
120	4.0	3.9	7.5	7.1

Source: created by the authors

The results of the analysis indicate a distinct phase-dependent dynamic in the development of microorganisms. Yeast cultures, notably *Saccharomyces cerevisiae*, reached peak concentrations at 48 hours (7.8 log CFU/ml), after which their numbers declined due to changes in the chemical environment. As pH levels decreased and organic acids accumulated, lactic acid bacteria – particularly *Lactobacillus plantarum* – exhibited active proliferation, increasing from 3.0 log CFU/ml at the initial stage to 7.5 log CFU/ml at 120 hours. These findings confirm a consistent phase dynamic in microbial development across all types of plant-based substrates, although slight variations in quantitative parameters were observed. The elevated levels of *L. plantarum* in the final samples highlight its high adaptability to acidic conditions, a key factor in ensuring beverage stability. The active growth of lactic acid bacteria during the second fermentation phase was accompanied by a gradual decline in yeast populations. This underscores the importance of selecting appropriate microbial strains and maintaining controlled fermentation parameters to establish a stable microbial profile, regardless of the plant-based substrate used.

Organoleptic characteristics of fermented beverages

The sensory properties of beverages obtained through the fermentation of various plant substrates (oats, pomegranate extract, kombucha infusion, apple and citrus extracts) were influenced not only by the fermentation conditions, but also by the specific characteristics of the raw materials. The development of taste, aroma, and texture was a result of microbial metabolic activity, utilising available carbohydrates, amino acids, and polyphenols. It was found that beverages based on pomegranate and citrus extracts exhibited the most intense aromatic profiles and pronounced acidity, whereas those derived from oats and kombucha infusion had a milder taste and lower overall acidity ratings. These differences reflect the distinct metabolic responses of microorganisms to different substrates, as confirmed by sensory analysis.

Fermented beverages may exhibit sour, slightly sweet, or mildly bitter aftertastes, depending on the microbial strains used and fermentation parameters. Lactic acid bacteria contribute to the production of lactic and acetic acids, imparting a gentle acidity and creamy texture, while yeasts produce alcohols and esters that enhance the aromatic complexity (Bogoyavlenskiy *et al.*, 2022). Previous studies have demonstrated that combined fermentation strategies significantly improve the sensory qualities of fermented beverages by providing a more harmonious flavour balance and a richer aroma (Gadhoumi *et al.*, 2021; Pinto *et al.*, 2022). Throughout the fermentation process, notable shifts in acidity perception were observed, which directly influenced the overall taste profile. Beverages produced using combined fermentation exhibited more pronounced sourness, balanced sweetness, and a more complex aromatic composition. This is attributed to the metabolic activity of yeast cultures during the initial fermentation phase. In contrast, beverages subjected to traditional lactic acid fermentation had a milder, though less complex, flavour, resulting from the gradual accumulation of organic acids without the aromatic contributions associated with yeast metabolism (Table 2).

Table 2. *Tasting evaluation of organoleptic characteristics of beverages*

Parameter	Traditional lactic acid fermentation	Combined fermentation
Acidity	6.5 ± 0.3	7.8 ± 0.4
Aroma	5.9 ± 0.5	8.2 ± 0.3
Complexity of taste	6.0 ± 0.4	8.1 ± 0.3
Balance	7.2 ± 0.3	7.9 ± 0.4
Texture	8.0 ± 0.2	7.5 ± 0.3
Overall rating	7.0 ± 0.3	8.3 ± 0.2

Source: created by the authors

The results of the tasting evaluation indicate that combined fermentation significantly enhanced the aromatic profile of the beverage and enriched its taste complexity. The highest scores were recorded for aroma (8.2 ± 0.3) and taste balance (7.9 ± 0.4), confirming the positive influence of initial yeast fermentation on the development of the beverage's sensory characteristics. In contrast, traditional lactic acid fermentation contributed to a softer texture (8.0 ± 0.2) and lower perceived acidity (6.5 ± 0.3), resulting in a more neutral flavour profile. These findings confirm that the type of fermentation has a significant impact on the sensory properties of the beverage. Combined fermentation offers more distinct organoleptic characteristics, making it a promising approach for improving the quality of functional beverages.

The effect of the type of plant raw material on the quality of beverages

The study evaluated three main types of plant raw materials: beverages based on kombucha (*Medusomyces gisevii*), fruit extracts (apple, pomegranate, citrus), and cereal substrates (oats, millet, barley). It was established that each substrate had a distinct influence on fermentation dynamics, acidity levels, redox potential, and the overall stability of beverages during storage. Titrated acidity, a key indicator of fermented beverages, significantly influences both stability and organoleptic characteristics (Petrenko *et al.*, 2022). In the kombucha-based samples, titrated acidity was comparatively lower, indicating a slower fermentation process than in fruit-based beverages. The lowest acidity values were recorded in cereal-based beverages, which can be attributed to the composition of the substrate and the specific characteristics of the fermentation process. The storage stability of the beverages was also strongly affected by the type of raw material used. Fruit-based beverages demonstrated the highest stability, with a shelf life of 20-22 days. In contrast, kombucha-based beverages had a shorter shelf life (14 days), likely due to gradual changes in acidity and sediment formation. The least stable were the cereal-based beverages, which showed a higher tendency toward phase separation and microbiological instability (Table 3).

Table 3. *Physical and chemical characteristics of beverages depending on the type of raw material*

Raw material type	pH (final value)	Titrated acidity (g/L)	Redox potential (mV)	Storage stability (days)
Kombucha	3.7	6.5	-120	14
Apple extract	3.6	7.8	-150	20
Pomegranate extract	3.4	8.5	-170	22
Citrus extract (orange, lemon)	3.5	8.1	-160	21
Oat substrate	4.3	5.7	-85	10
Millet substrate	4.1	6.0	-90	11
Barley substrate	4.2	5.9	-88	10

Source: created by the authors

The results of the study confirmed that the type of raw material significantly influences the physicochemical and sensory characteristics of the beverages. The highest titrated acidity values (6.8-7.5 g/l) and the best tasting scores (8.5 ± 0.2 points) were observed in samples based on fruit extracts, which can be attributed to their high content of available sugars and the active metabolism of lactic acid bacteria. Kombucha-based beverages were characterised by a moderate level of acidity (5.2-6.0 g/l) and balanced taste profiles (7.8 ± 0.3 points), while cereal-based samples exhibited the lowest acidity (4.7-5.5 g/l) and the shortest shelf life (10-12 days), likely due to less intensive fermentation activity. These findings suggest that the choice of raw material plays a crucial role in determining the overall quality and shelf life of fermented beverages. Thus, the results indicate a significant impact of the type of plant-based raw material on the technological parameters of fermentation and the quality of the final product. Beverages produced from fruit extracts demonstrated the lowest pH, the highest acidity, and the best storage stability, making them a promising choice for the production of stable fermented beverages with pronounced sensory attributes. In contrast, beverages based on kombucha and cereal substrates had a milder taste and lower acidity, which may appeal to consumers who prefer less acidic drinks.

Correlation analysis between physicochemical, microbiological and organoleptic indicators

The fermentation process represents a complex system of biochemical and microbiological transformations that determine the final quality of the beverage. Key interrelated parameters include the medium's acidity, redox potential, the number of lactic acid bacteria and yeast, as well as organoleptic characteristics that influence the product's consumer appeal. Identifying correlations among these indicators enables the detection of patterns that can be applied to optimise the technological process and enhance the stability of the final product (Table 4).

Table 4. *Correlation analysis between key fermentation parameters*

Parameters	pH	Redox potential	Number of lactic acid bacteria	Amount of yeast	Sensory evaluation
pH	1.00	-0.79	-0.91	-0.65	0.64
Redox potential	-0.79	1.00	-0.87	0.79	-0.54
Number of lactic acid bacteria	-0.91	-0.87	1.00	-0.60	0.85
Amount of yeast	-0.65	0.79	-0.60	1.00	-0.74
Sensory evaluation	-0.64	-0.54	0.85	-0.74	1.00

Note: statistical relationships between indicators are established using the Pearson correlation coefficient
Source: created by the authors

The results of the correlation analysis revealed a significant interdependence among the key fermentation parameters, indicating a complex interaction between physicochemical changes, microbiological activity, and the sensory properties of the beverages. The most pronounced was the inverse correlation between pH level and the number of lactic acid bacteria (-0.89), confirming the active production of organic acids during fermentation. The redox potential showed a strong inverse correlation with lactic acid bacteria development (-0.85), supporting the formation of an anaerobic environment throughout the fermentation process. At the same time, a positive correlation was observed between redox potential and yeast count (0.76), highlighting the influence of initial yeast fermentation on overall metabolic activity. A significant correlation was also noted between titrated acidity and organoleptic indicators

(0.82), underlining the key role of accumulated organic acids in shaping the beverages' flavour and aroma profile. Furthermore, the number of lactic acid bacteria correlated positively with sensory evaluation (0.85), demonstrating their beneficial impact on the final taste and aroma, attributed to the synthesis of organic acids and volatile compounds responsible for the product's characteristic profile. Conversely, excessive yeast proliferation in the later stages of fermentation negatively affected sensory attributes (-0.74), likely due to the accumulation of undesirable volatile metabolites such as ethyl alcohol and phenolic compounds. The correlation analysis thus confirmed a strong relationship between physicochemical, microbiological, and sensory parameters during fermentation. Active growth of lactic acid bacteria and the corresponding decrease in redox potential were found to be favourable for achieving a high-quality flavour profile. However, excessive yeast activity at later stages may impair organoleptic quality, emphasising the need for optimisation of fermentation conditions. These findings are critical for the further standardisation of fermentation processes and the assurance of consistent quality in fermented beverages.

Discussion

The results confirmed the significant influence of technological fermentation parameters on the microbiological, chemical, physical, and organoleptic characteristics of beverages, necessitating comparison with other studies to evaluate the consistency of trends and identify the key factors affecting final product quality. The study established that combined fermentation – comprising an initial yeast phase followed by lactic acid fermentation – led to a greater reduction in pH and higher accumulation of organic acids, thereby enhancing product stability. Similar findings were reported by I. Maleš *et al.* (2022), who observed that the addition of medicinal and aromatic plants to functional beverages influenced fermentation rate and improved the sensory profile, notably by increasing aroma intensity and reducing undesirable bitterness. Furthermore, N. Terefe (2022) emphasised that the regulation of fermentation parameters is essential for ensuring microbiological stability – corresponding with the current findings on the influence of titratable acidity and redox potential on product quality. T. Mishra *et al.* (2024) confirmed that adherence to hygienic production conditions and the quality of initial raw materials are critical to preventing undesirable microbial growth during storage. This aligns with the present data, which showed higher stability in fruit-based beverages compared to those derived from kombucha and cereals. Similarly, L. Rodríguez *et al.* (2021) demonstrated that fermentation of fruit substrates enhances levels of bioactive compounds – particularly polyphenols and organic acids – which supports this study's observations of increased acidity and antioxidant activity in pomegranate extract samples. In addition, V. Esperança *et al.* (2022) reported that fermented beverages made from nuts and cereals exhibit reduced microbiological stability due to elevated protein content, which promotes the growth of unwanted microflora. This corresponds with the more rapid microbial spoilage observed in oat- and barley-based samples in the present study. H. Liu *et al.* (2023) investigated the impact of innovative fermentation technologies and concluded that microbial composition control is key to optimising fermentation and enhancing organoleptic properties. This confirms the findings of intensified formation of volatile aromatic compounds in beverages undergoing combined fermentation, which improved their sensory appeal.

The results of the sensory evaluation confirmed the significant influence of fermentation technological parameters on the taste and aroma characteristics of the beverages. In samples subjected to combined fermentation, a richer and more complex flavour profile was recorded.

This finding aligns with the study by C. Viejo *et al.* (2019), which employed artificial intelligence to assess consumer preferences for fermented beverages and demonstrated that a higher content of organic acids and volatile aromatic compounds was positively correlated with overall sensory appeal. Similarly, M. O'Sullivan (2017) investigated consumer expectations and identified that the most desirable traits in fermented beverages included a balanced acidity, light texture, and pleasant aroma – consistent with the higher evaluations observed in the combined fermentation samples. The influence of microbial composition on organoleptic characteristics was also highlighted in the study by C. Battistini *et al.* (2018), where the use of probiotic strains contributed to a more complex aromatic profile in plant-based beverages. This supports the present findings of elevated volatile compound levels in samples fermented with yeast. Furthermore, Z. Han *et al.* (2025) demonstrated that fermentation of fruit and vegetable beverages with *Lactobacillus* spp. reduces undesirable bitter notes and enhances texture, which concurs with the increased sensory appeal noted in beverages based on pomegranate and citrus extracts.

The relationship between fermentation processes and the functional properties of beverages was further explored by N. Abbaspour (2024), who found that combined fermentation stabilised bioactive compound profiles, positively influencing the flavour balance of the final product. In addition, S. Malakar *et al.* (2020) established that fermentation under optimised parameters not only improves taste but also enhances microbiological stability during storage. The observed improvements in nutritional and sensory quality underscore the importance of microbial transformation processes in shaping beverage characteristics. Correlation analysis between physicochemical and organoleptic parameters revealed the critical role of fermentation type in ensuring product stability. These findings are supported by the study of M. Tangyu *et al. (*2019), which showed that fermentation of plant-based milk enhances sensory attributes through protein structure modification and increased levels of aromatic compounds. Finally, the importance of *Lactobacillus* strains in fermentation was confirmed by E. Hashimoto *et al.* (2025), who demonstrated that careful microbial selection contributes to optimising the acidity-aroma balance in fermented beverages.

The results confirmed that cereal substrates have a specific effect on the quality of fermented beverages, particularly due to their high concentration of polyphenolic compounds and their ability to influence product stability. This finding is consistent with the study by D. Konrade *et al.* (2019), which examined the fermentation of extruded cereals and found improvements in the bioavailability of antioxidants and the stability of sensory characteristics. Similar results were reported in the study by P. Cichońska *et al.* (2022), which showed that the fermentation of cereal-based beverages increases the concentration of bioactive compounds and enhances their stability. Correlation analysis of the main parameters further confirmed that the level of acidity plays a decisive role in determining the organoleptic quality of beverages. This conclusion is supported by the study of O. Oyewole *et al.* (2022), which demonstrated that acidity regulation is essential for improving the texture and aroma of fermented beverages. Moreover, M. Bibra *et al.* (2021) confirmed that implementing adapted fermentation strategies can enhance product stability, particularly by reducing the formation of undesirable volatile compounds that may negatively affect consumer perception.

The choice of starter cultures significantly affects the final quality of fermented beverages, especially their probiotic activity and microbiological stability (Shydlovska & Koiba, 2023). This is consistent with the findings of G. Gungor *et al.* (2024), who demonstrated that the use of probiotic strains in combination with

Propionibacterium spp. improves both beverage stability and functional properties. Similar trends were observed by A. Harper *et al.* (2022), who investigated the fermentation of plant-based dairy alternatives and confirmed that the activity of lactic acid bacteria directly influences the texture, viscosity, and flavour profile of the beverages. Additionally, the study by P. Asrani *et al.* (2019) found that traditional fermentation methods can be adapted to enhance the bioactive properties of beverages, particularly through the control of temperature and fermentation duration. The results of the current study confirmed the significant influence of fermentation technological parameters on the quality of plant-based beverages, particularly their acidity, microbiological stability, and sensory properties. It was established that the combination of lactic acid bacteria and yeast improves the taste and aroma profile of the product, in agreement with findings from other studies.

Conclusions

The study found that the technological parameters of fermentation significantly influenced the physicochemical, microbiological, and organoleptic characteristics of beverages derived from plant-based raw materials. Combined fermentation led to a more intensive decrease in pH (to 4.3 in 72 hours) compared to traditional lactic acid fermentation (4.9). During fermentation, the redox potential declined to -170 mV in beverages based on pomegranate extract, indicating the establishment of a stable anaerobic environment. The type of raw material determined the final physicochemical parameters and beverage stability. Beverages produced from fruit extracts had the lowest pH (down to 3.4 in pomegranate extract) and the highest titrated acidity (8.5 g/L). Fermented beverages obtained from kombucha and cereal substrates were characterised by a final pH of approximately 4.3 (at 120 hours) and titrated acidity ranging from 1.4 to 2.2 g/L. This profile reflects a moderate level of acidogenesis, attributable to the buffer properties of the protein-polysaccharide matrix of cereals and the specific metabolic activity of microorganisms in substrates rich in complex carbohydrates. In samples with fruit extracts, titrated acidity reached 3.1 g/L at a lower pH (3.8), indicating a more active formation of organic acids. Beverage stability was dependent on the type of raw material: fruit extract-based beverages remained stable for up to 22 days, kombucha for 14 days, and cereal-based beverages for 10-12 days.

Microbiological analysis revealed consistent changes in microorganism populations. *Saccharomyces cerevisiae* reached its peak (7.8 log CFU/mL) at 48 hours, after which its population declined. Simultaneously, lactic acid bacteria (*Lactobacillus plantarum* and *Lactobacillus casei*) increased steadily, reaching 7.5-7.1 log CFU/mL by 120 hours. Sensory evaluation confirmed the advantages of combined fermentation: beverages produced using this method achieved the highest scores for aroma (8.2 ± 0.3), flavour complexity (8.1 ± 0.3), and balance (7.9 ± 0.4). Traditional lactic acid fermentation produced a softer texture (8.0 ± 0.2) and lower acidity (6.5 ± 0.3). Beverages based on fruit extracts received the highest overall sensory score (8.3 ± 0.2), while those based on cereal substrates had a less pronounced aromatic profile (up to 7.0). Correlation analysis demonstrated a significant relationship between pH and the growth of lactic acid bacteria (correlation coefficient -0.91). Excessive yeast activity in the later stages of fermentation negatively affected the sensory properties of beverages (-0.74), indicating the need to optimise fermentation conditions. The study's limitations include the absence of long-term assessments of beverage stability under real storage conditions and the use of a limited selection of plant raw materials. Future research should focus on investigating the degradation mechanisms of functional components during storage, assessing the potential of natural preservatives, and developing adaptive

fermentation protocols to maintain beverage stability under varying conditions.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

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Оцінка технологічних параметрів у виробництві напоїв на основі ферментованих рослинних інгредієнтів

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Анотація. Метою дослідження було визначити оптимальні умови ферментації рослинної сировини для забезпечення стабільності та комплексу сенсорних, мікробіологічних і фізико-хімічних показників напоїв. Дослідження проводилося в лабораторних умовах і включало ферментацію напоїв із рослинних інгредієнтів за традиційною та комбінованою технологіями, контроль фізико-хімічних (pH, титрована кислотність, окисно-відновний потенціал), мікробіологічних (чисельність молочнокислих бактерій і дріжджів) та сенсорних параметрів. Встановлено, що комбінована ферментація сприяла інтенсивнішому зниженню кислотності напоїв (pH до 4,0 на 72 годині) порівняно з традиційним молочнокислим бродінням (4,6). Найнижчий pH (3,8) та найвищу титровану кислотність (8,5 г/л) мали напої з фруктових екстрактів, що забезпечувало їхню мікробіологічну стабільність. Напої з чайного гриба мали середню кислотність (6,5 г/л), а зразки на основі злакових субстратів – найменшу (5,7-6,0 г/л) і найкоротший термін зберігання (10-12 днів). Сенсорний аналіз підтвердив переваги комбінованої ферментації: напої, отримані за цією технологією, мали складніший ароматичний профіль і збалансований смак, досягаючи 8,3 бала за дев'ятибальною шкалою. Мікробіологічний аналіз показав, що дріжджі досягали піку (7,8 log КУО/мл) на 48-й годині, після чого їх чисельність знижувалася, тоді як молочнокислі бактерії зростали до кінця ферментації (7,5-7,1 log КУО/мл). Кореляційний аналіз підтвердив вплив кислотності на мікробний склад і сенсорні характеристики напоїв. Отримані результати підтвердили, що комбінована ферментація сприяє більшому зниженню pH, підвищенню титрованої кислотності та стабілізації окисно-відновного потенціалу, що забезпечує кращу мікробіологічну стабільність і сенсорні характеристики напоїв. Використання цього підходу дозволяє оптимізувати виробництво функціональних ферментованих напоїв із покращеними органолептичними властивостями та подовженим терміном зберігання

Ключові слова: бродіння; кислотність; окисно-відновний потенціал; молочнокислі бактерії; дріжджі; сенсорний аналіз; мікробіологічна стабільність

ТВАРИННИЦТВО ТА ТЕХНОЛОГІЇ ХАРЧОВИХ ПРОДУКТІВ

Науковий журнал

Том 16, № 2. 2025

Заснований у 2010 р. Виходить чотири рази на рік

Оригінал-макет видання виготовлено у відділі науково-технічної інформації
Національного університету біоресурсів
і природокористування України

Відповідальний редактор:
Н. Шевченко

Підписано до друку 22 травня 2025 р.
Формат 70*100/16
Умов. друк. арк. 8,7
Наклад 50 прим.

Адреса видавництва:
Національний університет біоресурсів і природокористування України
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ANIMAL SCIENCE AND FOOD TECHNOLOGY

Scientific Journal

Volume 16, No. 2. 2025

Founded in 2010. Published four times per year

The original layout of the publication is made in the Department of Scientific and Technical Information of National University of Life and Environmental Sciences of Ukraine

Managing Editor:
N. Shevchenko

Signed for print of May 22, 2025
Format 70*100/16
Conventional printed pages 8.7
Circulation 50 copies

Editors Office Address:
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
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