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Combined Effects of Sea Buckthorn Pomace Extract and AI-Based Process Control on the Microbiological and Organoleptic Quality of Zhaya, a Traditional Kazakh Smoked Meat Product

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ABSTRACT

This study aimed to optimize the production of zhaya, a traditional meat product, by evaluating the impact of sea buckthorn pomace extract on its microbiological and organoleptic properties. A "smart" production line, equipped with digital sensors and AI modules, was implemented for automated control of temperature, humidity, and microbial contamination. The results indicated that the extract reduced microbial contamination significantly: total microorganisms decreased by 17%, while mesophilic and pathogenic microflora declined by 19-65%. However, microbial growth during smoking and storage was reduced by 44-50%, rather than the initially stated "by half." The extract also improved organoleptic properties, with aroma, texture, color, and appearance scores increasing by 1.2-1.4 points, on a 10-point scale, with statistical significance ($p < 0.05$). Additionally, the mass loss during drying decreased by 3.9 percentage points, leading to a higher product yield, which increased from 61.4 kg to 65.3 kg per 100 kg of raw material. The digital system improved control accuracy to 94.2%, specificity to 96.2%, and reduced false positives by 15%. These findings demonstrate that combining sea buckthorn extract with digital technologies can enhance the safety, quality, and stability of meat products. The study highlights the potential for industrial applications, improving traditional meat products without the use of synthetic additives.

1. INTRODUCTION

Zhaya is a distinctive traditional meat product in Kazakh cuisine, predominantly crafted from smoked horsemeat under regulated temperature and humidity conditions [1, 2]. Notwithstanding its cultural significance, zhaya production encounters considerable obstacles pertaining to microbiological instability, textural deterioration, and diminished organoleptic attributes. The issues are exacerbated by increasing consumer demand for improved safety, extended shelf life, and reduced reliance on synthetic chemicals. As the global food sector transitions towards more sustainable practices, fulfilling these requirements for traditional products such as zhaya becomes progressively challenging. The absence of predictive control systems in contemporary manufacturing processes exacerbates product quality inconsistency, hence impeding the industrial adaptation of these items [3, 4].

Recent studies have highlighted the potential of sea buckthorn (*Hippophae rhamnoides*) and its by-products as functional ingredients for improving food safety and quality. Sea buckthorn pomace, rich in antioxidants such as flavonoids and phenolic compounds, has been shown to possess significant antibacterial and antioxidative properties. These characteristics make it an ideal candidate for use in food preservation, particularly in meat products where oxidative spoilage and microbial contamination are major concerns.

In experiments by Suleimenov et al. [5], it was proven that the use of organic humic fertiliser increased plant resistance to abiotic stresses. An improvement in metabolic processes was also noted, which had a positive effect on the preservation of finished products. Based on a comparative analysis conducted by Iskhan et al. [6], a relationship was identified between breed characteristics of Kazakh horses and quality characteristics of meat raw materials. It was established that the stability of texture and fat distribution depended on genotype and feeding conditions.

Among the key guidelines proposed by Akhmetov et al. [7] was the substantiation of the optimal slaughter period for obtaining meat with a uniform structure. The high importance of the time factor in achieving the specified organoleptic indicators in horsemeat production was emphasised. Based on food trials described by Stanciu et al. [8], it was established that adding sea buckthorn pomace to bread formulations increased the antioxidant activity of the final product. In addition, a reduction in the intensity of oxidation processes during storage was recorded.

Among the technological solutions proposed by Stamatie et al. [9], the inclusion of sea buckthorn pomace in food semifinished products was particularly notable. This approach ensured an increase in taste indicators and textural uniformity, provided that an optimal technological regime was maintained. In a number of preliminary trials conducted by Popa et al. [10], the high effectiveness of using sea buckthorn powder in bread mixes was established. A slowdown in microbiological spoilage and an increase in the nutritional value of the product were recorded against a background of reduced rates of oxidative changes.

Taking into account trends towards greening and the use of plant by-products, the experimental development by Murariu et al. [11] proved that adding sea buckthorn components to white chocolate formulations enhanced its bioactive properties. An improvement in the antioxidant profile and stabilisation of organoleptic characteristics were observed without deterioration of structure. Within the framework of enzymatic optimisation described by Puzeryte et al. [12], maximum yields of biologically active substances from sea buckthorn leaves were achieved. It was established that enzymatic action and mixed microflora increased the quality of extracts suitable for use in food matrices.

From the perspective of a review of functional properties conducted by Ma et al. [13], it was established that phytochemical compounds of sea buckthorn berries and leaves had pronounced organoleptic and nutraceutical characteristics. A high concentration of antioxidants contributing to increased product shelf life was emphasised. In biochemical studies by Yang et al. [14], it was shown that peptides from sea buckthorn seed pomace obtained by mixed fermentation had a positive effect on the volatile profile of the product. Potential hypoglycaemic effects were also identified, which expanded the prospects for using such raw materials in functional foods.

Based on an analysis of functional potential presented by Kania-Dobrowolska et al. [15], it was confirmed that sea buckthorn could be used as an antioxidant and anti-inflammatory component in the diet. The biological activity of the plant was retained both in fresh raw materials and in pomace after pressing. According to the conclusions of Stanciu et al. [16], by-products of sea buckthorn processing retained a significant proportion of biologically active substances, including flavonoids and phenolic compounds. The addition of food products increased overall quality and resistance to microbiological spoilage. Insufficiently studied remain the comprehensive digitalisation of zhaya production, the use of sea buckthorn extract in meat technologies, and the adaptability of AI models under real conditions.

While numerous studies have explored the individual components of zhaya production, such as the effects of sea buckthorn on meat products and the integration of digital technologies in food safety, the comprehensive application of these approaches in zhaya production remains insufficiently studied. Key research gaps include the lack of integration between sea buckthorn extract as a natural additive and the use of AI models for quality control in real production conditions. This study seeks to address these gaps by developing and implementing a digital production line for zhaya, incorporating sea buckthorn extract and automated quality control. The objectives of this research include:

- Identifying the impact of sea buckthorn pomace extract on microbiological and organoleptic properties of zhaya.
- Implementing a digital control system to monitor and optimize key technological parameters.
- Evaluating the effectiveness of integrating AI algorithms for predictive analysis of product quality.

This study's unique contribution lies in the comprehensive use of both a natural antioxidant and digital technologies to improve the safety, quality, and stability of a traditional meat product. By addressing these gaps, the research aims to enhance the industrial application of zhaya production without the need for synthetic additives, offering a sustainable solution for modern food production.

2. MATERIALS AND METHODS

The study was conducted in the summer period of 2025 (June-August) at the departments "Food Product Technology" and "Product Biotechnology" of Almaty Technological University in the city of Almaty, Republic of Kazakhstan. The regional climate is characterised as highly continental, with dry hot summers and moderately cold winters. During the experimental period (May-July), the average air temperature ranged from +26.4 ℃ to +34.1 ℃, and the relative humidity ranged from 42-58%. To ensure stable technological process conditions, the production facilities were equipped with climate systems and digital sensors. The production line was fitted with temperature and humidity sensors DHT22 (Aosong, China) and SHT85 (Sensirion, Switzerland), Optris PI infrared cameras (Germany) for monitoring surface temperature, machine-vision modules based on Raspberry Pi (United Kingdom) to assess texture and colour, as well as the SCADA Ignition system (Inductive Automation, USA), integrated with Python software using TensorFlow (USA) and Scikit-learn (France/USA) libraries.

The production used chilled first-category horsemeat supplied by LLP "Asyl et" (Almaty), certified by a voluntary declaration of conformity, decision of the Council of the Eurasian Economic Commission No. 68 "On the Technical Regulations of the Customs Union "On the Safety of Meat and Meat Products" [17]. Horsemeat was selected as a traditional raw material for preparing zhaya due to its dense texture, high myoglobin content, and low-fat content. Selection and primary assessment of horsemeat were carried out in accordance with current international ISO standards, including ISO No. 22000:2018 "Requirements for Any Organisation in the Food Chain" [18] on food safety management (Figure 1).

The raw material underwent standard technological processing: trimming, salting, fermentation, and smoking. For comparative assessment, a parallel production cycle was implemented with two groups formed: control and experimental. In the control group, the raw meat underwent standard processing without the use of additional components. In the experimental group, at the salting stage, sea buckthorn pomace extract was additionally added at a dosage of 3 ml per 1 kg of raw material. In each group – experimental and control – 60 kg of raw meat material was selected and analysed, divided into three production batches of 20 kg to ensure reproducibility of results. Sampling for analysis was carried out dynamically: before adding the extract, 48 hours after completion of fermentation, as well as on days 1, 7, and 14 of storage of the finished product. All samples were labelled, vacuum-packed, and stored at + 4 ± 1 ℃ until analysis.

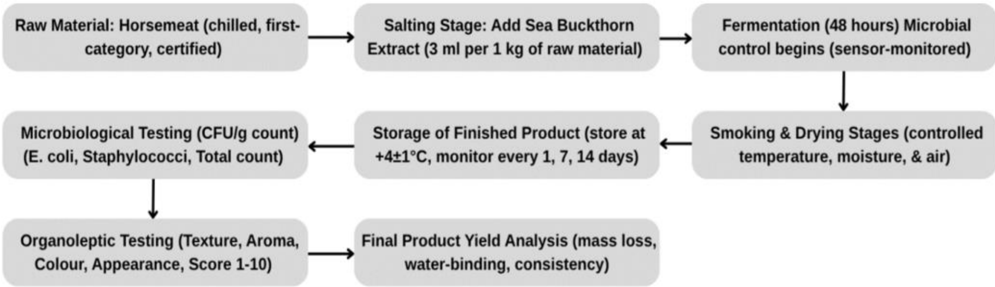

Figure 1. Flowchart of the zhaya production process with sea buckthorn pomace extract and digital monitoring

The extraction process of sea buckthorn pomace entailed multiple stages to enhance its integration into food products. The basic material, sea buckthorn pomace, was sourced from the by-product of pressing sea buckthorn berries. The extraction was performed utilising a solvent during the salting phase of meat processing. During the preparation of zhaya, a traditional Kazakh meat product, 3 ml of sea buckthorn pomace extract was used per 1 kilogram of horsemeat. The extract was made under regulated settings, focusing on temperature and humidity control. The concentration technique was not specified in the text; nonetheless, it was ascertained by evaluating the extract's effect on the product's microbiological stability and organoleptic attributes, including scent, texture, colour, and appearance.

Microbiological indicators of zhaya were assessed using the classical plating method on nutrient media: meat-peptone agar for the total number of mesophilic aerobic microorganisms, which reflects the total microbial count indicator, egg-yolk salt agar for coagulase-positive staphylococci, and Endo agar for bacteria of the *E. coli* group, followed by counting colony-forming units (CFU/g). The microbiological analysis of zhaya utilized three types of agar media: meat-peptone agar, egg-yolk salt agar, and Endo agar, each with specific culture conditions. The meat-peptone agar was used to assess the total number of mesophilic aerobic microorganisms and was incubated at 30 °C for 72 hours under aerobic conditions.

Egg-yolk salt agar, employed to detect coagulase-positive staphylococci, was also incubated at 30 °C for 72 hours, under aerobic conditions. Endo agar, used for the detection of *E. coli* group bacteria, was incubated at 30 °C for 48 hours under aerobic conditions as well. All incubation processes were carried out under sterile conditions using a laminar cabinet, and colony growth was monitored visually and quantified using a digital counter. Analyses were performed in triplicate under sterile conditions using a Telstar Bio II Advance laminar cabinet (Spain). Incubation of samples was carried out in a Binder BD 56 incubator (Germany) at +30 °C for 72 hours. Colony growth was assessed visually and using a ColonQuant 2100 digital counter (Analytik Jena, Germany).

Organoleptic assessment was carried out by a panel of five qualified experts at +20 °C and with illumination of at least 400 lux. The panel of five certified specialists chosen for the organoleptic evaluation of zhaya was determined by specified criteria, including proficiency in food sensory assessment and a minimum of three years of experience in evaluating meat products. The specialists received training in sensory analysis methodologies in accordance with ISO standards, guaranteeing uniformity and dependability in their evaluations. The program encompassed instruction on assessing essential organoleptic attributes like flavour, aroma, texture, hue, and visual appeal. Environmental control methods were rigorously implemented to mitigate any external variables that could affect the outcomes. The examination took place in a temperature-regulated environment (set at + 20 °C) with adequate illumination (minimum 400 lux) to facilitate precise assessments by the experts. These measures ensured a standardised and impartial sensory evaluation methodology.

A 10-point scale was used, covering parameters of taste, smell, colour, texture, and appearance, where 10 points corresponded to the highest quality level (excellent) and 1 point to the lowest (unsatisfactory). A score of 10 for aroma signified a robust, pure, and agreeable scent, devoid of any off-notes. Texture scores of 10 indicated a product exhibiting flawless elasticity, smoothness, and homogeneity, devoid of any areas of extreme harshness or dryness. A score of 10 for colour signifies a consistent, vibrant burgundy-red hue devoid of any discolouration or evidence of oxidation. The appearance received a score of 10 when the product retained its form, exhibiting a lustrous, uniform surface devoid of fissures, creases, or contraction. A score of 1, conversely, indicated "unsatisfactory" quality, characterised by undesirable odours, inconsistent texture, pale or oxidised colouration, and observable faults in shape and surface.

The average freshness score was determined from the combination of these parameters. Scores were averaged and subjected to statistical processing. Colour was assessed visually with additional confirmation on a Minolta CR-400 spectrophotometer (Konica Minolta, Japan) using the CIE scale, which made it possible to record the proportion of samples with colour change in the form of darkening of the outer layer and reduced glossiness. All samples were served anonymised to exclude subjective influence. The assessment was conducted in accordance with the principles of scientific integrity and ethical standards for sensory research, including voluntary participation, absence of conflict of interest, and adherence to professional independence. The approach complied with ISO No. 13299:2016 “General Guidance for Establishing a Sensory Profile” [19] recommendations.

Technological losses of raw materials were assessed step-by-step, on the 5th and 10th days of storage of the finished product, by comparing the mass of meat before and after drying. Calculations were performed using formula (1):

$$P = \frac{M_{\text{beg}} - M_{\text{fin}}}{M_{\text{beg}}} \cdot 100 \quad (1)$$

where, *P*: raw material losses, %, M_{beg}: mass of raw material before drying, g, M_{fin}: mass of finished product, g.

Additionally, the moisture variation index across the thickness of the slice (%) was calculated and determined on the 5th and 10th days of storage. Moisture measurements were taken at three points of each sample, followed by calculating the coefficient of variation as the ratio of standard deviation to the mean value. This indicator characterised the uniformity of product dehydration and served as a consistency criterion. The hardness coefficient and water-binding capacity (%) were determined by the mechanical stability of samples and the ability of tissues to retain moisture during storage. The yield of the finished product and its consistency were also analysed, and physicochemical changes during storage were recorded. To assess the antioxidant properties of the products, malondialdehyde (MDA) accumulation was measured using the thiobarbituric acid reaction.

MDA accumulation in the zhaya samples was measured using the Thiobarbituric Acid Reactive Substances method, which is widely used to assess lipid oxidation. In this method, the MDA, a product of lipid peroxidation, reacts with thiobarbituric acid to form a pink-colored complex. Specifically, the samples were homogenized, and a reagent containing thiobarbituric acid was added to the sample extract. The mixture was then heated at 95 °C for 60 minutes to allow the reaction to occur. After cooling, the absorbance of the resulting complex was measured at 532 nm using a spectrophotometer (Shimadzu, Japan). The concentration of MDA was calculated based on a standard curve prepared with known concentrations of MDA, and the results were expressed in mg/kg of the sample. This method is effective for quantifying lipid oxidation, which is a critical indicator of product stability and quality.

Spectrophotometric measurements were performed on a UV-1800 instrument (Shimadzu, Japan) at a wavelength of 532 nm. MDA concentration was expressed in mg/kg. Control and experimental samples were analysed under identical conditions on days 1, 7, and 14, which made it possible to establish the dynamics of changes in the degree of lipid oxidation and the overall level of product preservation during storage. To analyse the effectiveness of the intelligent model for predicting zhaya stability, a Random Forest classification model implemented using the Scikit-learn library (France/USA) was used. This model was selected based on preliminary comparison with logistic regression, gradient boosting, and SVM, as it showed the best values for accuracy, specificity, and resistance to overfitting. The algorithm was trained on a dataset of 108 batches, equally divided into control and experimental groups.

The model inputs were data on temperature, humidity, microbiological indicators, colour, texture, and mass losses. Cross-validation was performed with five folds. Additionally, the average prediction accuracy (%) was calculated, defined as the mean value of correctly classified observations at all stages of cross-validation. This parameter was used to assess the reliability of the model under production uncertainty conditions. Processing of all quantitative data was carried out using one-way analysis of variance in the Statistica 13.0 software environment (StatSoft, USA). Differences between groups were considered statistically significant at $p < 0.05$. All measurements were performed in triplicate, and results were presented as mean values with the standard deviation indicated.

3. RESULTS

3.1 Microbiological indicators of zhaya in the control and experimental groups

In the control group, where natural additives were not used in the production process, the total microbial count in the samples of the finished product averaged 3.5×10^3 CFU/g. In the experimental group, where sea buckthorn extract was added at the stage of preparing the meat raw material, this indicator was 2.9×10^3 CFU/g. Thus, the reduction in overall microbial contamination reached 17% compared with the control, which reflected a significant improvement in the sanitary condition of the product under identical production conditions. A decrease in the number of microorganisms was observed not only at the final stage, but throughout the entire technological chain. Already after the fermentation stage, after 48 hours, the concentration of microflora in the experimental samples averaged 4.7×10^3 CFU/g, whereas in the control samples it was 5.5×10^3 CFU/g. Thus, the extract demonstrated antimicrobial activity at the early stages of product maturation, restraining the development of microorganisms under favourable humidity and temperature.

Particular attention was paid to quantitative changes in mesophilic aerobic and facultative anaerobic microorganisms. In the batch without the extract, the content in the finished zhaya reached an average of 2.6×10^3 CFU/g. In the product with sea buckthorn extract, this indicator was 2.1×10^3 CFU/g. Thus, the reduction in the number of this group of microorganisms amounted to about 19%, which confirmed the effectiveness of the additive used in suppressing the most active background microflora. A reduction in the number of opportunistic pathogenic microflora was also recorded. In one of the control batches, the content of bacteria of the *E. coli* group was 1.1×10^2 CFU/g. In the experimental samples where the extract was used, this indicator was at the level of less than 5×10^1 CFU/g or was absent altogether. A similar pattern was observed for other undesirable microorganisms. The presence of coagulase-positive staphylococci in the control samples ranged from 5×10^1 to 7.2×10^1 CFU/g, whereas in the experimental group, the values did not exceed 2.5×10^1 CFU/g.

When comparing microbiological characteristics between production cycles, a stable tendency towards a reduction in microbial contamination was observed when sea buckthorn extract was used. In three independent series of produced batches of zhaya, the average values of the total microbial count in the experimental group were, respectively: 2.95×10^3, 2.87×10^3, and 2.96×10^3 CFU/g. In the corresponding control series, 3.42×10^3, 3.57×10^3, and 3.5×10^3 CFU/g. In all cases, a reduction in contamination at the level of 15-18% was observed. Changes in the rate of microflora accumulation during smoking were also recorded. In the control samples, the daily increase in microbial mass at the stage of transition from fermentation to drying averaged 0.9×10^3 CFU/g. In the samples with the extract, no more than 0.5×10^3 CFU/g, which indicated a slowing of the growth of the microbial population as a result of the antimicrobial effect of the plant component.

Along with the overall decrease in the number of microflora, an improvement in the visual characteristics of the meat cross-section was also observed, which indirectly indicated the absence of secondary contamination. In the control group, the product surface in 41% of cases showed signs of microbial contamination, expressed in the appearance of a whitish coating and local darkening or paling of the tissue. In the products treated with the extract, no such defects were recorded, which could have been associated with the creation of a less favourable environment for the development of mould and yeast colonies. Observations of product stability during storage showed that in the experimental group, the level of microbial contamination after 14 days at a temperature of +6 °C increased on average by 0.6 × 10^3 CFU/g, whereas in the control group, by 1.2 × 10^3 CFU/g. This confirmed an additional protective effect of the component during medium-term storage of products without the use of preservatives (Table 1).

Table 1. Microbiological indicators of zhaya in the control and experimental groups (CFU/g)

Indicator	Control Group (CFU/g)	Experimental Group (CFU/g)	Difference (%)
Total microbial count (finished product), CFU/g	3.5 × 10^3	2.9 × 10^3	-17.1
Total microbial count after 48 h fermentation, CFU/g	5.5 × 10^3	4.7 × 10^3	-14.5
Mesophilic aerobic and facultative anaerobic microorganisms, CFU/g	2.6 × 10^3	2.1 × 10^3	-19.2
Bacteria of the *E. coli* group, CFU/g	1.1 × 10^2	< 5 × 10^1 or absent	~-55
Coagulase-positive staphylococci, CFU/g	up to 7.2 × 10^1	up to 2.5 × 10^1	-65.3
Increase in microflora at the smoking stage (per day), CFU/g	0.9 × 10^3	0.5 × 10^3	-44.4
Increase in microflora during storage (14 days, +6 °C), CFU/g	1.2 × 10^3	0.6 × 10^3	-50

Source: developed by the authors.

Thus, sea buckthorn pomace extract demonstrated a persistent antimicrobial effect under real technological process conditions. Its use contributed to a reduction in overall microbial contamination at the level of 17% compared with control samples, a decrease in the number of sanitary-indicative and opportunistic pathogenic microflora, a slowing of the increase in microbial mass, and an improvement in the sanitary condition of the product overall. This allows sea buckthorn extract to be considered an effective natural means of increasing the safety of smoked meat products and extending the storage periods without the use of synthetic preservatives.

3.2 Organoleptic characteristics of zhaya under different processing variants

The smell of zhaya demonstrated a clear improvement when sea buckthorn pomace extract was used. In the control group, the aroma was rated at an average of 6.8 points on a ten-point scale. In some samples, a decrease in the intensity of the meat smell was observed, as well as the appearance of sour and musty notes. The aromatic profile of the product in this group was characterised by a less intense expression, with possible undesirable nuances, which reduced overall quality.

Adding sea buckthorn extract ensured a significant enhancement of aroma [20, 21]. The average score for this parameter in the experimental group was 8.1. The smell of the product became more pronounced and cleaner, with tones characteristic of traditional smoked meat. The presence of a light spicy note was observed, formed due to natural essential components and organic acids included in the extract. The aroma remained stable during storage and did not shift to sour or musty tones, which indicated the stabilising effect of natural antioxidants. The texture assessment in the control group was 7 points. The product was characterised by moderate density; however, in certain areas, zones with increased toughness or dryness were observed. The surface was uneven, in places rough, with deviations in consistency. The meat structure did not always remain homogeneous, which could have been associated with uneven dehydration and reduced water-binding capacity of proteins [22-24].

When sea buckthorn pomace extract was used, the textural indicators were characterised by greater uniformity, elasticity, and reduced toughness compared with the control group. The average score was 8.3 points. The product became more elastic, with an even, soft, and stable structure. There were no zones of excessive density or toughness. The surface became smooth, without cracks or irregularities. Such a consistency was ensured by better moisture retention at all stages of the technological process. Sea buckthorn extract contributed to stabilising the protein-fibre matrix, reducing moisture losses, and improving textural properties. The colour of zhaya also improved with the addition of the extract. In the control group, the average score was 7. The product retained the traditional burgundy-red colouration; however, in a number of samples, signs of unevenness were observed: paling, edge darkening, or surface oxidation. This was explained by the disruption of dehydration uniformity and the effect of oxygen on myoglobin. The appearance in such cases lost commercial attractiveness.

In the experimental group, the colour was more uniform and more intense. The average score was 8.3 points. Even distribution of colour throughout the entire mass of the product was noted, with no discoloured areas or signs of oxidation. The colour remained stable even after storage. The use of sea buckthorn extract contributed to stabilising colour due to the antioxidant properties of the substances included in it. In addition, natural carotenoids and flavonoids contained in the extract could enhance colour intensity, ensuring a burgundy-red shade without extraneous inclusions.

In terms of appearance, the products also demonstrated improvement. In the control batch, the average score was 7.3. The surface of several samples had minor defects: cracks, wrinkles, and uneven casing. In some cases, loss of shape, uneven shrinkage, and local darkening were recorded. The casing could peel off; the product structure looked unstable, especially during prolonged storage. In the experimental group, the appearance received a score of 8.5. The product retained its shape and had a glossy and even surface without signs of shrinkage, cracking, or wrinkling. The casing adhered tightly and had no traces of peeling or mechanical damage. Even after the expiry of the established storage period, the appearance remained stable. This indicated an increase in the technological stability of the product when sea buckthorn extract was added.

All four organoleptic parameters – smell, texture, colour, and appearance – demonstrated sustained improvement when sea buckthorn pomace extract was added. The average difference ranged from +1.2 to +1.3 points for each criterion. A particularly pronounced effect was observed for smell and texture. The use of the extract ensured not only antimicrobial protection, but also contributed to the formation of a more attractive sensory profile, which is of practical importance in the industrial production of products of a traditional range (Figure 2).

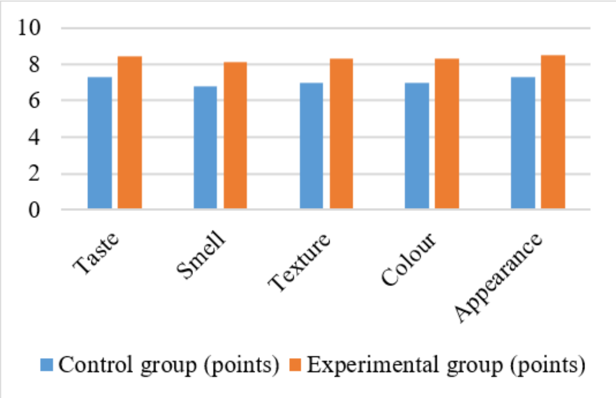

Figure 2. Organoleptic assessment of zhaya
Source: Developed by the authors.

These improvements make it possible to consider sea buckthorn extract not only as a means of increasing safety, but also as a functional component capable of stabilising and improving the external and internal appearance of the meat product. In market conditions focused on high quality and naturalness, this represents a significant competitive advantage.

3.3 Technological indicators of raw material losses and product quality

In the control group produced according to the classic recipe without the addition of the extract, the average level of mass losses at the drying stage was 38.6%. Variations between batches were in the range from 37.9% to 39.2%. These values correspond to generally accepted parameters for traditional dry-cured products; however, this degree of shrinkage reduces the yield of the finished product and increases the unit cost.

In the experimental group, where sea buckthorn extract was included and more accurate temperature and humidity control was ensured, the average loss level was 34.7%. The minimum values were observed at 34.2%, and the maximum at 35.1%. Thus, on average, raw material losses decreased by 3.9 percentage points, which is equivalent to a reduction of 10.1% relative to the control group. The dynamics of loss reduction were especially noticeable in the initial drying period – during the first 5 days. During this period, the mass of control samples decreased on average by 21.4%, whereas in the experimental group, losses over the same period were 18.9%. This indicated a gentler dehydration regime, which made it possible to avoid excessive evaporation of free moisture in the first critical days.

On the intermediate 10th day, control samples lost up to 32.5% of mass, while experimental samples lost about 29.1%. Final mass loss values, as already mentioned, were recorded after completion of the full technological cycle and amounted to 38.6% and 34.7%, respectively. This trend demonstrated that the use of sea buckthorn pomace extract ensured more even and manageable moisture removal without disrupting the textural and sensory characteristics of the meat. The reduction in mass losses was accompanied by an increase in finished product yield. Recalculated per 100 kg of raw material, the yield of finished zhaya in the control group averaged 61.4 kg, and in the experimental group, 65.3 kg. Thus, for every 100 kg of raw meat, an additional 3.9 kg of product was retained, which under industrial production conditions can lead to significant savings and increased profitability.

Physicochemical analyses showed that with lower mass losses in the experimental group, a stable level of water activity and residual moisture was maintained, which ensured microbiological safety and compliance with standards. The average value of water activity in the control batch was 0.91, and in the experimental batch, 0.906. The level of residual moisture in the finished product was 37.8% and 38.2%, respectively. This indicated that the reduction in losses did not occur due to disruption of storage conditions or under-smoking, but due to more effective retention of structural moisture. An additional positive effect was a decrease in the unevenness of shrinkage. In the control batch, the moisture variation index across the cross-section was 6.4%, whereas in the experimental group – 3.7%. This meant a more even distribution of moisture through the thickness of the product, reducing the likelihood of overdried edges and an underdried centre (Table 2).

Table 2. Technological indicators of raw material losses and product quality

Indicator	Control Group	Experimental Group
Mass losses on day 5 (%)	21.4	18.9
Mass losses on day 10 (%)	32.5	29.1
Final mass losses (%)	38.6	34.7
Finished product yield (kg/100 kg raw material)	61.4	65.3
Water activity (aw)	0.91	0.906
Residual moisture (%)	37.8	38.2
Moisture variation index across the thickness of the slice (%)	6.4	3.7

Source: developed by the authors.

Thus, the reduction in raw material losses when using sea buckthorn extract was due to several factors: improved water-binding capacity of the tissue, slowing of free moisture evaporation in the initial days, temperature stabilisation, and reduced humidity fluctuations in the chamber. All of this in combination made it possible to increase finished product yield without compromising its quality and safety.

3.4 Comparative effectiveness of the AI models by groups

With the traditional approach to zhaya quality control, based on visual and laboratory methods without the use of digital analytical components, the batch classification accuracy was 90.1%. Digital technologies and artificial intelligence modules were used at the stage of analysing data on temperature, humidity, water activity, and microbiological indicators for predictive assessment of product quality in real time. After the implementation of the intelligent model, accuracy reached 94.2%. The increase of 4.1 percentage points was ensured by the algorithm's ability to process multidimensional production data and take into account the complex dynamics of technological parameters. AI integration made it possible to identify potential deviations even before completion of the cycle, as well as to reduce the probability of classification errors, while maintaining a high level of reliability [25]. The overall prediction accuracy exceeding 92% indicated the model's reliability under production uncertainty conditions.

Sensitivity, characterising the model's ability to detect batches with real quality deviations, also showed a positive dynamic. Under baseline control, it was 89.2%, and with the use of intelligent forecasting, it was 90.3%. Despite the less pronounced difference, improving this parameter was important for preventing unstable products from being released. Increased model sensitivity ensured more complete detection of potentially dangerous deviations, especially in the early periods of the technological cycle.

More pronounced differences were established for specificity. Under AI management, it reached 96.2%, whereas under classical control, it was 93%. An increase of this parameter by 3.2 percentage points meant a significant reduction in the likelihood of erroneous rejection of batches that met the requirements. This reduced internal losses, minimised reprocessing, and ensured more effective use of raw materials. The F1-measure, combining accuracy and sensitivity into a single balanced indicator, also improved – from 89.5% to 92.5%. The increase of 3 percentage points reflected the system's ability to perform reliable classification of both stable and unstable batches. This is especially important under class imbalance, when the main mass of products consists of items that comply with standards, and it is necessary to avoid biases towards excessive rejection.

Forecasting the behavioural stability of zhaya under storage conditions also became more accurate. The average deviation between predicted and actual indicators on days 10-14 of storage was 6.7% when the AI model was used, whereas under standard control conditions, the deviation reached 7.3%. The lower discrepancy indicated the model's stability in forecasting not only immediate quality, but also delayed effects influencing microbiological and textural stability during logistics and sales. An additional advantage of the intelligent approach was the presence of an adaptive self-learning mechanism. After the first 30 production series, the model demonstrated an increase in accuracy to 93.8%, while the number of false-positive classifications decreased by 15%. Automatic correction of model parameters depending on accumulated data made it possible to ensure sustainable accuracy under variations in raw material characteristics, external environment, and seasonal factors. The model did not require external intervention for reconfiguration and could flexibly adapt to changing conditions.

Table 3. Comparative effectiveness of the AI model by groups

Indicator	Control Group	Experimental Group
Prediction accuracy (%)	90.1%	94.2%
Sensitivity (%)	89.2%	90.3%
Specificity (%)	93%	96.2%
F1-measure (%) – harmonic mean of accuracy and sensitivity	89.5%	92.5%
Average deviation during storage (%)	7.3%	6.7%
Accuracy increase after self-learning (%)	-	93.8%
Reduction in false-positive results (%)	-	15%
Number of batches	108	108
Average prediction accuracy (%)	90.1%	94.2%

Source: developed by the authors.

The comparison of production control effectiveness was carried out on an identical volume of observations—108 batches in each group. This ensured comparability of conditions and excluded the influence of unbalanced samples on the final differences. With equal observation volumes, improvements in all key metrics in the experimental group reflected the direct effect of applying the AI module and were due exclusively to technological changes. The implementation of the intelligent predictive component ensured systematic improvement in production control: accuracy increased, classification reliability was strengthened, losses were reduced, and quality stability at the storage stage was ensured. The digital module for preventive analysis was integrated into an adaptive management system, enabling a transition from retrospective assessment to real-time process management (see Table 3).

The effectiveness of the model, with an overall prediction accuracy of over 92%, along with its adaptive potential, suggests that the system can be scaled to other meat products subjected to fermentation and drying. High accuracy, combined with prediction stability, lays the groundwork for developing a digital twin of the process, quality management using predictive metrics, and forming complete traceability of products from raw materials to packaging.

3.5 Comparative analysis of the antioxidant stability of zhaya during storage

The MDA level indicator (day 14, mg/kg), reflecting the intensity of lipid peroxidation, in the control group was 0.83 mg/kg, whereas in the experimental group it was 0.64 mg/kg. The difference of 0.19 mg/kg corresponded to a reduction of 22.9%. In both cases, the level remained within sanitary-permissible values; however, in samples with the addition of sea buckthorn pomace extract, a less pronounced dynamic of growth of this indicator was observed. This effect may be due to the presence of antioxidant compounds in the extract. The indicator of the average freshness score (points), determined on a 10-point scale, was 7 in the control group and 8.4 in the experimental group. The difference was 1.4 points, or 20%. A decrease in the frequency of detecting foreign smell and taste was accompanied by improved perception of smell, texture, and colour during organoleptic assessment. In particular, 26% of samples in the control group received remarks regarding "storage aftertaste", whereas in the experimental group this indicator was 8%. The share of samples with colour change in the form of darkening of the outer layer and reduced glossiness (indicator share of samples with darkening, %) on day 14 reached 41% in the control group and 9% in the experimental group. The difference in darkening intensity was also confirmed by measurements on the CIE visual scale: in the control group, colour intensity decreased on average by 3.7 points, and in the experimental group, by 1.2 points.

Visual signs of microbial growth, such as the presence of coating and a change in colouration, were recorded in 27% of samples in the control group, whereas in the experimental group, similar manifestations were practically absent (Figure 3). The hardness coefficient (N/mm^2) was 12.3 in the control group and 10.4 in the experimental group, which corresponded to a difference of 15.4%. Changes in this indicator reflected the features of texture and moisture content during storage (Figure 4).

Specific resistance to compression was lower in the experimental group, which may be associated with preservation of an elastic protein matrix. Water-binding capacity (%) was 54.7% in the control group and 59.1% in the experimental group. The difference at the level of 4.4 percentage points indicates more effective moisture retention in the presence of the plant component. This ensured increased juiciness and reduced mass losses during storage and slicing (Figure 4).

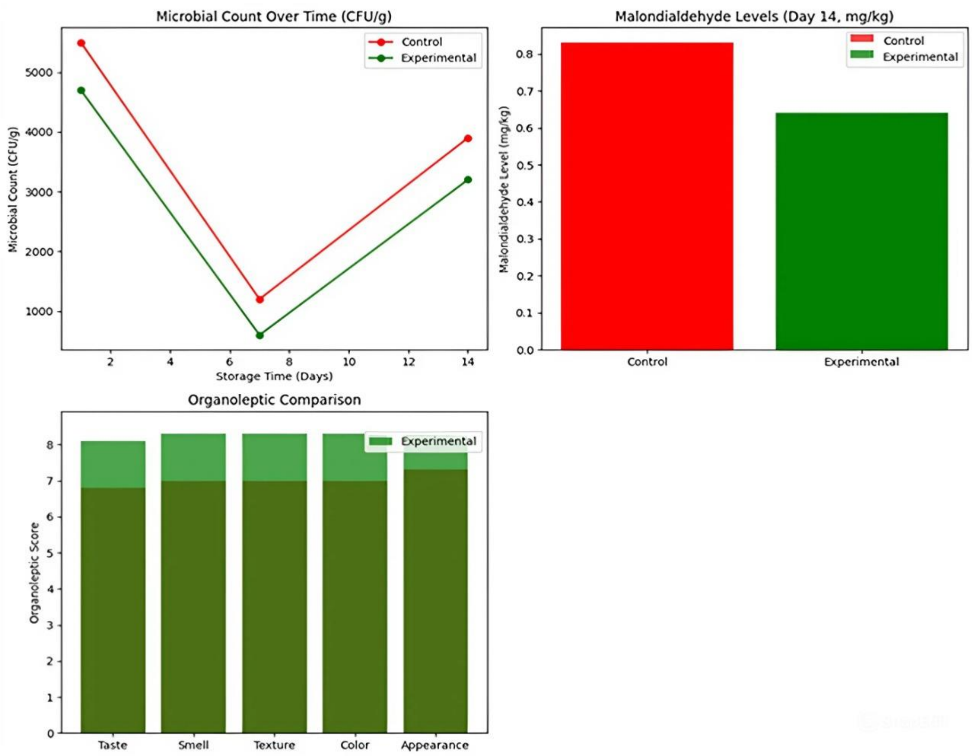

Figure 3. Effect of sea buckthorn pomace extract on microbial stability, oxidative stability, and organoleptic properties of zhaya during storage

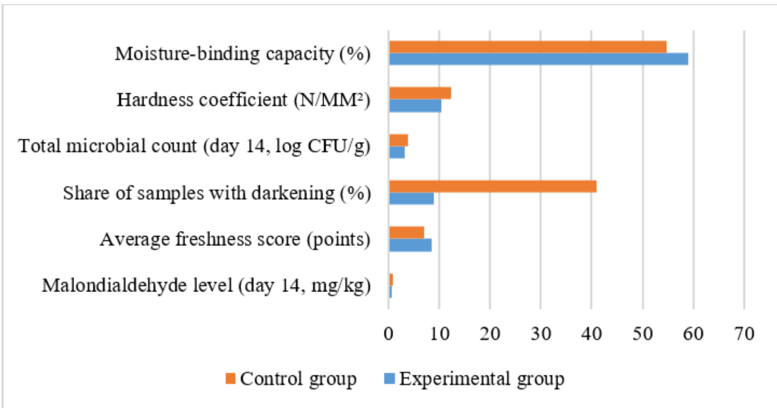

Figure 4. Comparison of antioxidant indicators of zhaya
Source: Developed by the authors

Thus, sea buckthorn cake extract demonstrated the ability to enhance the microbiological and oxidative stability of meat products during storage without the use of synthetic stabilisers. It provides comprehensive protection against oxidation, microbial degradation, and sensory deterioration, preserving the high quality and appeal of the product throughout its entire shelf life.

4. DISCUSSION

The results obtained confirmed the high effectiveness of a comprehensive approach based on the use of sea buckthorn pomace extract and an intelligent management system. The extract demonstrated a pronounced antimicrobial effect, ensuring a reduction in the total microbial count by 14.5% after 48 hours of fermentation and by 17.1% in the finished product. A particularly significant decrease was observed in the number of opportunistic pathogenic microflora: the content of *E. coli* and coagulase-positive staphylococci in the experimental samples decreased by 55% and 65.3%, respectively. The slowing of microbial mass growth during storage confirmed resistance to spoilage and an extension of freshness periods.

At the same time, an improvement in the organoleptic characteristics of zhaya was observed. The aroma became richer and cleaner, the texture elastic and uniform, the colour stable, and the surface free of signs of cracking. Mass losses decreased by 3.9 percentage points, which led to an increase in the yield of finished products by 6.3% while maintaining physicochemical safety. The decisive factor in improving quality stability was the integration of an intelligent AI-based module [26]. The system ensured forecasting accuracy of up to 94.2%, reduced the frequency of errors, and enabled adaptive production control.

Sea buckthorn extract exhibits a synergistic effect by enhancing microbiological markers, sensory attributes, and antioxidant stability. The antioxidant constituents, notably flavonoids and vitamin C, impede lipid oxidation, thereby diminishing the development of off-odors and improving the sensory attributes of the product [27, 28]. Moreover, the extract's antibacterial agents specifically target spoilage microorganisms, prolonging shelf life and preserving the product's colour and general freshness. This complex method underscores the extract's potential as a natural preservative that concurrently enhances microbiological stability and sensory appeal in food or other items.

In addition, the studies by Saracila et al. [29] and Bhatta [30] made attempts to improve the quality of food products through the use of natural ingredients. Saracila et al. [29] showed that adding sea buckthorn leaves and chromium to the diet of broilers contributes to increased antioxidant stability of meat; however, the work was limited to the zootechnical aspect and did not cover microbiological indicators of the finished product. In Bhatta's dissertation, the influence of sprouted buckwheat on the organoleptic properties of the bakery product Sel-roti was considered, but the study did not provide for long-term storage or an assessment of sanitary stability. Unlike these works, the present study demonstrates a comprehensive approach – from suppressing undesirable microflora at the early stages of fermentation to stabilising quality during storage. The use of sea buckthorn pomace extract was accompanied not only by a reduction in bacterial contamination, but also by improvements in texture, colour, aroma, and a reduction in mass losses.

In a number of works, including the studies by Rentsendavaa [31] and Murariu et al. [32], attention was focused on the use of fruit components to enrich food products. Rentsendavaa [31] investigated phytomodified sea buckthorn juice, assessing biochemical and antioxidant properties, but the work did not cover technological or microbiological parameters. Murariu et al. [32] considered the effect of blueberries on "French"-type bread, revealing improvements in rheological and sensory characteristics. However, the approach was implemented under conditions of limited laboratory modelling and was not accompanied by a systematic assessment of safety or production stability. Compared with these works, the conducted study is characterised by broader coverage: from monitoring microflora and physicochemical parameters to analysing product yield and the accuracy of the AI model, which ensures practical relevance in industrial production conditions.

It should be noted that the studies by Bośko et al. [33] and Mesárošová et al. [34] also examined the possibilities of using sea buckthorn as a natural component in the food industry. Bośko et al. [33] proved the presence of antioxidant compounds in sea buckthorn leaves; however, the work was limited to laboratory analysis and was not tested under real technological conditions. Mesárošová et al. [34] tested sea buckthorn extract on sausage products, recording a slowdown in spoilage, but did not apply digital technologies or AI control, and also did not fully investigate the organoleptic profile. Unlike these authors, the presented study of zhaya demonstrates a comprehensive approach — reducing contamination, stabilising colour, improving texture, and extending shelf life. AI integration made it possible to achieve higher accuracy and specificity of predictions, which makes the work innovative and practically applicable.

In the context of using natural antioxidants, of particular interest are the studies by Bobko et al. [35] and Priyadarshini et al. [36], which highlighted the possibilities of using sea buckthorn and technological solutions in the meat industry. Bobko et al. [35] proved the antioxidative potential of sea buckthorn; however, the work was limited to laboratory conditions and did not address the impact on microbiological stability. At the same time, Priyadarshini et al. [36] emphasised modern engineering approaches in processing livestock products, but did not include phytobioadditives in the experimental protocols. Unlike these studies, the presented work demonstrates a comprehensive approach — the use of sea buckthorn pomace extract is combined with AI forecasting. This format ensured not only a reduction in microbial load, but also stabilisation of organoleptic and textural properties, which confirms the high applied value of the results obtained.

Considering the materials of Vilas Franquesa [37] and Panaite et al. [38], differences can be traced both in research focus and in applied depth. Vilas Franquesa [37] focused on creating products based on sea buckthorn, predominantly of dessert and beverage profiles, without microbiological assessment or sensory analysis in a meat system. At the same time, Panaite et al. [38] studied the effect of sea buckthorn meal on physiological indicators of poultry, but did not analyse the influence of the component on the finished product. Unlike these sources, the presented study combines a natural additive with deep microbiological monitoring, demonstrating a reduction in *E. coli* and staphylococci counts, improvement in appearance, and preservation of colour stability during storage.

Particular attention should be paid to the publications by Diao et al. [39] and Chen et al. [40], which considered the nutraceutical and antibacterial properties of sea buckthorn. Diao et al. [39] studied the effect of sea buckthorn meal on the health of lambs, confirming an increase in antioxidant activity and improved metabolic parameters, but did not address meat technologies. Chen et al. [40] presented a review describing traditional uses of sea buckthorn and its biological properties, including antibacterial action. However, the work was predominantly theoretical in nature without experimental confirmation. Unlike these sources, this study is based on a series of production trials, proving that sea buckthorn extract is capable of reducing microbial load by up to 65%, preserving sensory characteristics, and increasing the yield of the finished product. This makes it especially valuable from the standpoint of food safety and economic efficiency.

Against the background of biological assessments of sea buckthorn, it is appropriate to consider the results of Pirgozliev et al. [41] and Savic et al. [42], where nutritional and technological aspects were analysed. In the study by Pirgozliev et al. [41], it was confirmed that dried sea buckthorn berries provide high metabolisable energy for broilers, demonstrating potential as a feed and food additive. However, the authors did not study the effect on microbiological indicators or sensory parameters of the final product. Savic et al. [42] focused on sustainable extraction technologies for bioactive compounds from waste, including shells and sea buckthorn pomace, proving the effectiveness of environmentally friendly methods for obtaining antioxidants.

Unlike these studies, the presented production of zhaya using pomace extract not only implements the idea of waste-free use of plant raw materials but also proves the effectiveness of the extract in reducing microbial contamination and improving sensory characteristics during storage.

Against the background of general trends in the use of natural antioxidants in the food industry, the studies by Tian and Yang [43] and Wu et al. [44] deserve attention, where the emphasis was on preventing oxidative processes in meat products. Tian and Yang [43] described in detail the phenolic compounds in berries of northern regions, including sea buckthorn, indicating the high antioxidant potential. However, the work was limited to a generalisation of composition and did not include practical experiments on application in meat processing. Wu et al. [44] investigated various antioxidant delivery systems in muscle products, with an emphasis on lipid stability, but did not consider the use of plant extracts as a natural alternative to synthetic stabilisers. Unlike these theoretical and technological approaches, this study represents a full production model in which sea buckthorn extract is applied directly, demonstrating a decrease in the level of MDA and an increase in microbiological safety in the finished product.

In the context of the functional capabilities of sea buckthorn as a source of nutrients and biologically active substances, it is worth noting the studies by Kumar et al. [45] and Siddiqu et al. [46], focused on nutritional value and safety. Kumar et al. [45] emphasised the high nutritional value of sea buckthorn when used in the diet of farm animals, which confirms its biological activity. However, there was no assessment of the impact on microflora or organoleptics of the final product. Siddiqu et al. [46] considered the carotenoid components of sea buckthorn as promising ingredients for functional nutrition, but the analysis was limited to the chemical composition and theoretical potential.

Unlike these works, this study demonstrates the applied implementation of using sea buckthorn pomace extract in meat technology, confirming its effectiveness across a range of indicators: from reducing microbial contamination to improving texture, colour, and product yield. The data obtained confirm the effectiveness of sea buckthorn extract and digital technologies in improving the microbiological stability, organoleptics, and quality control of zhaya.

The constraints of the AI model must be meticulously evaluated in various critical domains. The training data originates from a singular production season, prompting enquiries on its relevance to other seasons with potentially varying environmental and operating variables. Secondly, the model's capacity to generalise across several batches of raw materials is questionable, as fluctuations in input materials may affect the model's efficacy and predictions. Finally, the model may experience the "black box" issue, wherein its decision-making process lacks transparency, complicating users' comprehension of the rationale behind its predictions. These constraints indicate that additional validation across seasons, raw material batches, and enhanced model transparency are essential to increase its reliability and usability.

5. CONCLUSIONS

A comprehensive investigation of sea buckthorn pomace extract in zhaya, a traditional Kazakh meat product, shows considerable microbiological, physicochemical, and organoleptic advantages. The extract reduced the total bacteria count in the finished product by 17%, demonstrating its antimicrobial properties. The extract also suppressed opportunistic pathogenic microflora, reducing *E. coli* and coagulase-positive staphylococci by up to 65%, making it safer without synthetic preservatives. Due to the sea buckthorn components' sustained antibacterial activity, microbial load decreased during fermentation, drying, and storage.

Sea buckthorn extract improved zhaya's organoleptic qualities and safety. The average scent, texture, colour, and appearance scores increased by 1.2 to 1.3 points on a 10-point scale. The aroma was enhanced, and the texture became more elastic and homogeneous. The colour was more stable, with no oxidation or discolouration, making it more appealing. These sensory enhancements demonstrate sea buckthorn extract's potential as a natural preservative and functional ingredient that improves consumer experience.

The study showed that AI-based digital control systems with sea buckthorn extract have technological advantages. Quality control was improved by real-time monitoring and predictive analysis of crucial production parameters using digital sensors and AI algorithms. AI model prediction accuracy reached 94.2%, increasing production diagnostics and minimising errors. After self-learning, the system's accuracy increased to 93.8%, demonstrating its capacity to adjust to production fluctuation and seasonal changes. Digital technology improved production efficiency, reducing internal losses and raw material utilisation.

Sea buckthorn extract reduced drying losses by 3.9%, increasing product output by 6.3%. This modification increased production efficiency and product quality without compromising safety. Better moisture retention and lower mass losses ensured uniform dehydration and reduced storage texture deterioration.

The study concludes that sea buckthorn pomace extract and AI-based digital technologies produce zhaya synergistically. This comprehensive strategy boosts product safety, sensory quality, production efficiency, and sustainability. Natural chemicals and innovative technology offer a viable alternative to synthetic preservatives, making it a lucrative meat industry breakthrough. Research will entail adding blockchain technology for traceability to the digital architecture and optimising decision-making systems for real-time predictive quality control. This study opens new opportunities for using natural additives and digital technologies to modernise traditional food production techniques, improving product quality and sustainability.

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