INNOVATIVE APPROACHES IN FOOD PROCESSING AND SUSTAINABILITY

Collective monograph

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ABSTRACT

Improvement of gluten-free granola production technology in the restaurant segment

This study focused on developing granola recipes using rice, buckwheat, and amaranth flakes combined with freeze-dried fruits (peach, strawberry, cherry, fig) and nuts (almond, hazelnut). Twelve formulations were tested, all classified as low-glycemic index products (below 55), making them suitable for diabetic and dietary use. The selected recipe demonstrated improved nutritional value, enhanced sensory qualities, and supports the diversification of functional foods aligned with healthy eating trends.

A multi-criteria strategy for assessing the quality of frozen raw cherry fruits

A multi-criteria optimization method identified the best cherry cultivars for freezing based on chemical, physical, and sensory traits. Geometric convolution helped select varieties with high quality and minimal losses. The study proposes quality indicators for frozen fruits, highlighting the impact of varietal differences. These results support zero-waste strategies and sustainable use of fruit resources.

Chemical composition and properties of vegetable oil blends

This study developed four vegetable oil blends with balanced omega-3 to omega-6 fatty acid ratios, combining olive, rapeseed, sunflower, linseed, and corn oils. The blends were evaluated for acid, peroxide, and iodine values to assess quality and oxidative stability. Results confirmed that the oils maintained favorable fatty acid profiles and stable quality, making them suitable for culinary use and supportive of health-oriented diets.

Development and characterization of ice cream containing vegetable oils

A technology for producing ice cream with vegetable oils as alternatives to milk fat has been developed, offering a product enriched with unsaturated fatty acids. The effects of sunflower, linseed, and sesame oils on texture, flavor, and nutritional value were analyzed. Key physicochemical properties, emulsion stability, and sensory characteristics were evaluated. Technological processes such as emulsification, stabilization, and freezing were optimized. The findings support the creation of nutritionally enhanced, plant-based ice cream with improved consumer appeal.

Compositional analysis and potential of buckwheat and oats as functional food ingredients

In this work, a comprehensive analysis of buckwheat and oat powders was carried out, including sieve analysis, infrared spectroscopy, X-ray fluorescence

analysis and gas chromatography with mass spectrometry. The study confirmed the unique nutritional profile of buckwheat and oat. The results can be used in the field of functional food, pharmacology and nutrition to develop products with high biological activity.

Justification and development of biotechnology of cooked sausage products for health purposes

This study aimed to reduce sodium intake and minimize the use of sodium nitrite in sausage production. A recipe for "Ozdorovchi" sausages was developed using 1.0% blood plasma protein, 0.5% citrus fiber, and 15 g/100 kg rosemary extract. The combined effect of plant- and mineral-based ingredients allowed for a reduction in nitrite content while improving functional, technological, and nutritional properties. The results confirm the feasibility of creating health-oriented sausages with enhanced safety and biological value.

Optimization of goose meat quality through oat and alfalfa-based feed additives

This study examined the effects of incorporating vegetative parts of oats and alfalfa into the diet of Legard Danish geese on the quality of meat during frozen storage. Replacing 50% of green mass with an oat–alfalfa mixture improved water-holding capacity and reduced thawing losses. Meat from the experimental group showed lower lipid peroxidation and higher levels of vitamin E and β-carotene. Enhanced fatty acid profiles, including more oleic acid and a better ω-6/ω-3 ratio, were observed, along with increased levels of essential amino acids. These results highlight improved oxidative stability and nutritional value of goose meat.

Reducing losses during storage of fruit vegetables: regulation of postharvest metabolism

This review explores modern strategies for reducing postharvest losses in fruit vegetables by regulating oxidative metabolism during storage. It focuses on cold stress responses – such as membrane damage and antioxidant imbalance – in perishable crops like tomatoes, peppers, and cucumbers. The article highlights integrated approaches combining physical treatments with bioactive compounds, including phytohormones and antioxidants. Emphasis is placed on species-specific responses and the importance of understanding tissue physiology to optimize storage and improve cold tolerance.

Essential oils in pig diet as a means of improving pork quality

This study examined the effects of the feed additive "Activo" on the lipid metabolism of pigs, revealing significant improvements in meat quality. The experimental group showed reduced levels of lipid peroxidation products and favorable shifts in fatty acid composition – specifically, lower stearic and pentadecanoic acids and

increased oleic acid. These changes enhanced the antioxidant status, thermal stability, and organoleptic properties of the meat, indicating the additive's potential to improve pork quality through lipid profile modulation.

Changes in quality parameters of sweet peppers during low-temperature storage after freezing

This study examined how long-term freezing affects sweet pepper quality. Water distribution, vitamin C, acids, and carotenoids decreased, while phenolics and pectin composition changed. Sugar content varied by variety. Cryogenic freezing best preserved tissue and sensory qualities, particularly in Atlant and Sonechko. The results help optimizes freezing and storage processes.

Sunflower lecithin as an alternative to soy lecithin: technological approaches to improving its rheological, sensory and functional properties

This study developed strategies to improve the technological properties of sunflower lecithin as a non-GMO alternative to soy lecithin. Deodorization using ≥ 40% ethanol effectively removed unwanted flavors and odors, while calcium salts (e.g., calcium acetate and orthophosphate) helped maintain lecithin liquidity. Decolorization with 0.7% hydrogen peroxide at 90°C for 120 minutes reduced color intensity by over 70%. Phospholipid fractionation revealed phosphatidylcholines as most prone to thermal darkening. These methods enhance sunflower lecithin's functionality for food industry applications.

Use of asparagus waste to fortify bakery products

This study explores the use of asparagus processing waste – specifically, basal spear parts – as a nutritional ingredient in bakery products. Freeze-dried asparagus powder was found to be rich in phenolic compounds, proteins, and micronutrients. Replacing up to 10% of whole-grain spelt flour with asparagus powder produced bread with improved nutritional value and good sensory properties. This approach supports waste reduction and offers a functional ingredient for health-oriented, low-carb, or gluten-free baked goods.

Innovative potential of sea buckthorn pectin in providing textural properties to food and pharmaceutical products

This study highlights the innovative potential of sea buckthorn pectin (Hippophae rhamnoides cv. "Leikora") in enhancing the structural and rheological properties of food and pharmaceutical systems. The pectin demonstrated a high thickening capacity and unique viscous flow behavior, influenced by activation enthalpy and entropy across concentrations. Its incorporation into meat-vegetable pastes improved texture, stability, and matrix cohesion. Sea buckthorn pectin thus represents a promising functional ingredient for developing stable, high-quality formulations with tailored rheological profiles.

Innovative technology for high-quality functional alcoholic beverages based on tea-aromatic raw materials with antioxidant activity

This study confirms the potential of antioxidant-rich water-alcohol infusions of yerba mate, green tea, and citrus peel for creating functional alcoholic beverages. Citrus-based infusions showed the highest antioxidant activity and sensory appeal. An optimal 20/75/5% mate/tea/citrus blend offered a balanced flavor and received high sensory ratings. A final beverage formulation with brandy, syrup, and flavor enhancers was developed at 20% alcohol. The findings support commercial use of these infusions in health-oriented drink innovations.

Technology improvement of cooked sausage products with the addition of non-traditional raw materials

This study examines the enrichment of cooked hake-based fish sausages with chicken meat, spelt flour, dried vegetables, cuttlefish ink, and red caviar to enhance nutritional and functional properties. Three formulations showed increased protein content, better texture, and water-holding capacity. Garlic-enhanced samples had the highest oxidative stability after 10 days. Sensory scores improved to 4.6 versus 3.8 in the control. The results support using unconventional ingredients in functional fish sausage production.

Keywords

Rresource-saving technologies, functional food, functional alcoholic beverage, food product enrichment, antioxidants, bioactive compounds, nutrient, vitamins, essential fatty acids, biological value, nutritional value, pseudo-cereals, buckwheat, oats, granola, gluten-free, nuts, freeze-dried fruits, asparagus, vegetable powder, vegetable raw materials, red caviar, cuttlefish ink, olive oil, rapeseed oil, corn oil, sunflower oil, linseed oil, sesame oil, fatty acids, fatty acid composition, sausage products, rosemary extract, bacterial preparation, sea salt with luminaria, pork, feed additive, meat quality, geese, alfalfa, amino acids, fruit, fruit vegetables, sweet pepper, storage, freezing, chilling injury, oxidative stress, postharvest metabolism, storage technologies, heat treatment, ice cream, emulsion, texture, physicochemical properties, organoleptic properties, rheological properties, sunflower lecithin, sea buckthorn pectin, geometric convolution criteria, tea-aromatic raw materials.

CIRCLE OF READERS AND SCOPE OF APPLICATION

This monograph *"Innovative approaches in food processing and sustainability"* is intended for a diverse and interdisciplinary audience involved in the study, development, application, and regulation of modern food technologies. The publication brings together a collection of research-based innovations and practical solutions, offering new insights into the improvement of food quality, safety, nutritional value, shelf life, and sustainability.

The content will be of particular relevance to the following groups:

Academic researchers and scientists working in food science and technology, nutrition, biotechnology, postharvest physiology, and functional food development. The monograph presents experimental data, methodological approaches, and applied innovations that can support further research and encourage collaboration across disciplines.

University lecturers, PhD and undergraduate students pursuing degrees in food technologies, agronomy, biochemistry, food engineering, public health, and hospitality management. The book can serve as a supplemental academic resource that bridges fundamental science and practical applications, supporting coursework, research projects, and thesis writing.

R&D specialists and process engineers in the food industry who are engaged in the design, optimization, and modernization of food production lines. The chapters offer tested technologies and prototypes related to ingredient modification, alternative formulations, waste valorization, and enhancement of sensory, nutritional, and rheological properties.

Managers and technologists from agricultural and food processing enterprises, particularly those involved in small- and medium-sized businesses aiming to adopt innovative, cost-effective, and sustainable solutions. The proposed technologies, including the use of non-traditional raw materials, food fortification with waste-derived ingredients, and natural preservatives, offer realistic options for process improvement and added value creation.

Start-up founders, innovators, and entrepreneurs in the areas of green food, smart food systems, and functional product development. The technological concepts and case studies described in the monograph provide inspiration and scientific backing for novel product lines focused on plant-based, gluten-free, low-waste, or health-oriented food products.

NGO representatives and community organizations involved in promoting healthy diets, circular economy models, and environmental stewardship. The reuse

of agro-industrial by-products, the incorporation of bioactive compounds, and the development of nutritionally enhanced foods directly support the principles of sustainable development and responsible consumption.

By integrating scientific research with practical implementation, this monograph offers a valuable base of knowledge for advancing innovation in food processing. It is not only a reference for current trends but also a catalyst for future developments aimed at improving global food systems.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Innovations for the sustainable development of food systems

Olesia Priss

In modern world, the food industry finds itself at the intersection of scientific and technological progress, environmental challenges, and increasing consumer demands. Issues of food safety, quality, and functionality are of particular importance in the context of ensuring food security, supporting healthy lifestyles, and preserving natural resources. Urbanization, climate change, demographic shifts, and pandemics necessitate new approaches to the production, processing, and storage of food raw materials. These global challenges require researchers and practitioners to develop innovative, environmentally sustainable, and economically viable technologies.

In this context, the collective monograph *"Innovative approaches in food processing and sustainability"* is devoted to reviewing, analyzing, and summarizing recent advances in food technology aimed at improving product quality, functionality, and safety. Particular attention is given to the development and implementation of innovative solutions across various sectors of the food industry – from the production of gluten-free products and functional beverages to the efficient utilization of secondary raw materials and reduction of food losses.

This publication draws on the principles of sustainable development and reflects key global trends in the food sector. Among the main directions shaping modern food production are the use of functional ingredients, development of plant-based alternatives to traditional food products, implementation of zero-waste strategies, and the application of digital and smart technologies to enhance quality control and optimize production processes.

The monograph aims to present cutting-edge scientific developments, technological solutions, and practical recommendations that contribute to the advancement of food processing across a wide range of products. It represents the joint efforts of researchers, engineers, and technologists from various academic institutions and enterprises with expertise in food chemistry, biotechnology, postharvest processing, microbiology, agrotechnology, and food process engineering.

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The structure of the monograph encompasses five thematic areas:

1. Development of functional and health-oriented food products:

– technological aspects of producing gluten-free granola for the restaurant sector, aligned with modern trend of healthy eating and catering to consumers with dietary restrictions;

– evaluation of buckwheat and oats as functional ingredients capable of increasing the biological value of food products;

– development and characterization of ice cream containing vegetable oils to offer enhanced nutritional profiles;

– technological improvement of cooked sausage products with the addition of non-traditional raw materials aimed at increasing functionality and nutritional value;

– development of innovative technologies for functional alcoholic beverages based on tea-aromatic raw materials with antioxidant activity.

2. Improvement of raw materials and animal-based products:

– optimization of goose meat quality through the use of oat and alfalfa-based feed additives to enhance nutritional and sensory properties;

– use of essential oils in pig diets as a tool for improving pork quality.

3. Processing of plant-based raw materials and enhancement of ingredient properties:

– study of the chemical composition and properties of vegetable oil blends, opening new opportunities for creating products with improved sensory and functional attributes;

– evaluation of sunflower lecithin as an alternative to soy lecithin, focusing on improving the rheological, sensory, and functional properties of food;

– development and application of sea buckthorn pectin in forming the texture of food and pharmaceutical products.

4. Postharvest handling and storage of fruit and vegetable products:

– multi-criteria strategies for assessing the quality of frozen raw cherry fruits, contributing to improved storage efficiency and product shelf life;

– regulation of postharvest metabolism in fruit vegetables to minimize storage losses;

– study of changes in quality parameters of sweet peppers during low-temperature storage following freezing.

5. Rational use of food resources and zero-waste technologies:

– utilization of asparagus processing waste to fortify bakery products, serving as an example of sustainable, waste-free food processing.

This monograph establishes a solid scientific foundation for further research and contributes to the practical implementation of technologies that not only ensure

high product quality but also reduce losses, promote efficient resource use, and enhance the nutritional value of food products.

The editorial team is confident that the materials presented will be of value to a wide audience of specialists – from researchers and educators to industry professionals and decision-makers – who are engaged in the development of the food sector, implementation of sustainable and technologically advanced solutions, and improvement of public health and well-being.

CHAPTER 1

Improvement of gluten-free granola production technology in the restaurant segment

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Abstract

Granola is a popular product among supporters of healthy eating due to its high fiber, vitamin, and mineral content.

This study aimed to obtain popular breakfast cereals – granola – using various ingredients. It researched twelve recipe compositions based on rice, buckwheat and amaranth flakes, freeze-dried peach, strawberry, cherry, and fig as well as almond and hazelnut nuts. The granola recipe contained two different sweeteners (Jerusalem artichoke syrup and maple syrup). The sensory properties of the samples were evaluated.

The study confirmed that the energy value of all the proposed granola recipes per 100 g is nearly identical, ranging within 352...389 kcal/100 g, which meets the established nutritional standards. The recipes containing buckwheat flakes exhibited higher energy values, while rice-based granola had a slightly lower energy value. However, this difference was not significant. The developed recipes belong to the category of low-glycemic index products (below 55 units), making them suitable for individuals with diabetes and for use in dietary nutrition.

The developed recipe contributes to increasing nutritional value, improving organoleptic properties, and expanding the range of functional food products, such as granola, that meet modern requirements for healthy eating.

Keywords

Granola, gluten-free, pseudo-cereals, freeze-dried fruits, nuts, Jerusalem artichoke syrup, maple syrup, glycemic index.

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1.1 Gluten-free products: demand, production, and scientific development

The modern food market is experiencing a steady increase in demand for functional and specialized products, particularly gluten-free ones. This trend is driven by the growing number of consumers following a gluten-free diet due to medical conditions such as celiac disease and gluten sensitivity, as well as a conscious choice in favor of a healthy lifestyle [1]. As a result, the restaurant segment is forced to adapt its offerings and implement innovative production technologies.

Granola is a popular product among the supporters of healthy eating due to its high fiber, vitamin, and mineral content. However, traditional granola often contains ingredients that may include gluten, such as oat flakes, wheat, or barley components [2], limiting its accessibility for individuals with gluten intolerance.

Despite the availability of gluten-free alternatives on the market, most of them are produced on an industrial scale and may contain preservatives, stabilizers, and flavor enhancers, which reduce their nutritional value and benefits. At the same time, the restaurant segment has the opportunity to offer fresh, high-quality gluten-free granola, developed using original recipes with natural ingredients.

Recent studies also confirm that the restaurant segment is a leader in implementing innovations in the food industry due to broader technological capabilities, availability of qualified staff, and higher consumer expectations. A significant number of consumers who follow a gluten-free diet report a lack of gluten-free options on restaurant menus, creating barriers to eating out. Moreover, studies indicate a growing demand for healthy and functional products among consumers, highlighting the need to expand the range of gluten-free dishes in restaurants [3]. Unlike cafés or food trucks, restaurants are able to ensure consistent quality and presentation of complex functional meals, such as gluten-free granola, which comply with modern healthy eating trends.

In this regard, the relevance of this study is based on the development of recipes and the improvement of production technology for gluten-free granola. This will expand the product range in the restaurant segment, ensure high quality, and meet modern healthy eating standards.

In 2022, the global market for gluten-free products was estimated at 6.45 billion USD, and it is expected to grow at a compound annual growth rate (CAGR) of 9.8% from 2023 to 2030. The primary factors driving this market expansion include increased awareness of disease prevention, particularly for cardiovascular diseases, diabetes, obesity, chronic lung diseases, and metabolic syndrome. An additional catalyst for market growth was the COVID-19 pandemic, which significantly increased the demand for gluten-free products. This trend is caused by consumers' growing

focus on their health and well-being. During the pandemic, interest in highly nutritious food products greatly increased, further contributing to the popularity of gluten-free products [4].

The number of individuals suffering from gluten intolerance is rising worldwide, simultaneously increasing the demand for products suitable for a gluten-free diet. Recent scientific research in the field of gluten-free food products demonstrates significant progress in the development of alternative ingredients and production technologies. This category includes pseudo-cereal crops, which are a valuable source of nutrients. They are characterized by a high protein, fiber, vitamin, and mineral content and are naturally gluten-free. This makes them particularly beneficial for individuals with celiac disease or gluten sensitivity. In addition to high nutritional value, pseudo-cereals have beneficial health properties, in particular, they contribute to a reduction in the risk of developing cancer, diabetes, arterial hypertension, and cardiovascular pathologies. Their antioxidant properties are attributed to the presence of phenolic compounds that can reduce oxidative stress [5].

Due to their unique nutritional and functional properties, underutilized pseudo-cereal crops have significant potential for the development of innovative "smart" food products. The most nutritionally rich representatives of this group include amaranth, buckwheat, and quinoa. The protein content of these crops ranges from 9 to 21%, making them a valuable source of plant protein [6].

Researchers also focus on the use of gluten-free grain crops such as amaranth, quinoa, buckwheat, and corn, which have high nutritional value and improve the texture and taste characteristics of the final product. Buckwheat, associated with bioactive components, provides health and nutraceutical benefits. Bioactive components extracted from buckwheat can be used in the pharmaceutical industry to treat various health-related conditions [7]. Buckwheat is also a rich source of starch, while amaranth seeds contain 8–16% dietary fiber. The lipid content in quinoa and amaranth is 2.3 times higher than in wheat and buckwheat [5]. The protein content in amaranth varies from 12 to 24%, depending on the variety and genotype. Its amino acid profile closely resembles that of an ideal protein, with a notable high content of lysine – an essential amino acid, that is typically deficient in most plant proteins [8].

Granola and breakfast cereal flakes are produced using extrusion technology, which is also widely applied to produce other types of snacks. However, the high-fat content of amaranth complicates its use in the production of extruded products, since fat has a significant lubricating effect, which limits the degree of expansion during extrusion [9].

To improve the technological properties and ensure the quality characteristics of the final product, it is recommended to extrude amaranth with the addition of starch.

In addition, the creation of nutritionally balanced extruded food products requires combining amaranth with other cereals, in particular rice, which provides an optimal macronutrient composition [10].

Studies have shown that pseudo-cereals are promising raw materials for the production of gluten-free breakfast cereals. In vitro predictive glycemic index assessments have confirmed that extruded products containing pseudo-cereal ingredients had a significantly lower content of rapidly and slowly digestible carbohydrates compared to control samples. This indicates the potential for using pseudo-cereal flour to regulate the glycemic response to extruded breakfast cereals [10].

Amaranth-based gluten-free granolas were developed, receiving high sensory evaluations and demonstrating appropriate physicochemical and nutritional characteristics. Additionally, inulin and oligofructose were used to improve the quality of amaranth-based bars, which positively affected their sensory properties [10].

Studies also confirm the importance of a balanced composition of gluten-free products to ensure the appropriate level of proteins, fats, and carbohydrates. The use of natural sweeteners, such as honey, agave syrup or date syrup, allows to increase the nutritional value of gluten-free granola without adding refined sugar. The increasing prevalence of diseases related to excessive sugar consumption poses a serious health risk. Many scientific studies have confirmed the correlation between high sugar consumption and an increased risk of developing cardiovascular diseases, obesity, and type 2 diabetes. In this regard, there is a growing demand for sugar-free alternatives or natural sweeteners such as low-calorie sugar substitutes, honey, grape molasses, and others [11]. However, honey loses its beneficial properties at high temperatures during granola baking.

Maple syrup is a delicacy prepared by boiling the sap obtained from various species of maple trees, mainly the sugar maple. Compared to other natural sweeteners, maple syrup is considered a better alternative to refined sugar due to its high concentration of phenolic compounds and minerals. The presence of organic acids (e.g. malic acid), amino acids and essential amounts of minerals including potassium, calcium, zinc and manganese make maple syrup unique [12].

Helianthus tuberosus L., or Jerusalem artichoke, appears to be a superfood that provides human health benefits at the level of the digestive, gastrointestinal, and dermatological systems. It is suitable for diabetic patients due to its high inulin content and is commonly used in hypocaloric diet due to its low carbohydrate content. In fact, 5–15 g per day is beneficial, with an evident prebiotic effect. Despite the science-based potential, the cultivation and consumption of Jerusalem artichoke remain limited at the global scale due to insufficient awareness among both consumers and producers [13].

Jerusalem artichoke (*Helianthus tuberosus L.*) belongs to the sunflower plant family and originates from North America. It produces high-yielding tubers that store inulin as an energy source. The content of this fructan in the tubers ranges from 8–21% [13]. Due to the β (2 $\rightarrow$ 1) bonds, inulin cannot be digested by intestinal enzymes, so it can be successfully used for the development of functional foods [14]. On the other hand, inulin-rich carbohydrates obtained from Jerusalem artichoke tubers have been shown to promote the growth and probiotic properties of some *Lactobacillus* strains [14].

Fruit drying is an essential step in granola production, as dried fruits retain most of the vitamins, minerals, and antioxidants found in fresh fruits [15]. Freeze-dried fruits and berries are produced by lyophilization, a technology of drying by deep freezing and subsequent removal of moisture under vacuum conditions. This method allows to preserve the maximum amount of nutrients, aroma, color, and structure of the product, which distinguishes it from traditional drying methods [16].

Pre-cooling of fruits is an important post-harvest processing step, which ensures the preservation of quality, slows down spoilage processes, and extends the shelf life of fruits. The choice of the optimal cooling method depends on the physiological characteristics of the fruits, storage conditions and economic feasibility [17, 18].

The production process of freeze-dried fruits and berries consists of several key stages. Firstly, fruits and berries are thoroughly washed, cut if necessary, and then the seeds or cores are removed. Then, prepared fruits and berries are frozen at ultra-low temperatures (–40…–50°C). This contributes to the formation of small ice crystals inside the cells. It minimizes damage to the cell membrane and overall structure. After freezing, the product is dried in a vacuum (freeze-drying). Frozen fruits are placed in a vacuum chamber, where moisture evaporates without turning into a liquid state (sublimation), bypassing the melting stage. This preserves the structure, color, taste, and nutrients of berries and fruits. Then the products are subjected to final drying (removal of residual moisture) at a temperature of +30…+50°C. Additional removal of residual moisture is necessary to ensure long-term storage. The process lasts from 8 to 24 hours, depending on the type of product. The finished product is hermetically packaged to prevent moisture absorption from the air [16].

Freeze-dried fruits and berries have numerous benefits. Thus, up to 95% of vitamins and trace elements are preserved, natural taste and aroma are quickly restored upon contact with water, and they have a long shelf life of up to 1–2 years. Freeze drying has proven to be the most effective and innovative method for preserving antioxidant properties. After the sublimation cycle, the final moisture content of the material is only 2–5% of the initial one, ensuring maximum preservation of beneficial properties and the production of high-quality product. This method is

promising for preserving the quality of raw materials during drying and preserving its medicinal properties [19].

Freeze-dried products are widely used in the food industry, sports, and tourist nutrition, as well as in the manufacture of baby food, muesli, desserts, and confectionery.

Considerable attention is paid to studying the impact of various technological approaches on the quality of gluten-free products. Studies show that the use of fermentation improves the organoleptic properties and digestibility of gluten-free products [20].

In addition, natural antioxidant-rich ingredients can extend the shelf life of granola without using synthetic preservatives. Foods rich in natural antioxidants include dried fruits and seeds, e.g. walnuts, almonds, hazelnuts, chia seeds, flax seeds; cocoa and dark chocolate with a high cocoa content; green tea and red tea (rooibos); spices, e.g. turmeric, ginger, oregano, parsley, cinnamon; vegetable oils, e.g. olive oil, flaxseed oil, sunflower oil; and red wine [21].

Thus, modern scientific developments in gluten-free technologies aim to improve the quality, nutritional value, and taste characteristics of products, which is an important aspect when developing new recipes for the restaurant segment.

1.2 Development of a gluten-free granola recipe

This scientific research aimed to develop a recipe and improve the technology for producing gluten-free granola in the restaurant segment. The main research objectives were to develop variants of experimental recipes for gluten-free granola; to produce experimental samples; to conduct a tasting evaluation of the experimental samples; to determine their energy value and glycemic index; based on the results obtained, to select the optimal recipe composition and improve the production technology.

Raw materials selected for the production of gluten-free granola included amaranth, buckwheat, and rice flakes; freeze-dried cherry, peach, fig, and strawberry, as well as almond and hazelnut kernels. All raw materials were of industrial origin, specifically: amaranth flakes produced by AmarantBio (Ukraine), rice and buckwheat flakes – Agricom Group (Ukraine), freeze-dried fruit and berry ingredients – Vitberry (Ukraine), Jerusalem artichoke syrup – Erdapfel (Ukraine), maple syrup – Vertmont (Canada), and nuts – Borges (Spain) and Targroch (Poland). The use of industrially produced raw materials ensured standardized quality and reproducibility of experimental conditions.

The first stage of modelling the gluten-free granola recipe involved the selection of analogue. For this purpose, an analysis of existing samples was conducted,

in particular, recipes used in industrial analogues. An analogue chosen for modification contained: oat flakes – 100 g, butter – 20 g, raisins – 30 g, walnuts – 80 g, honey – 20 g.

The specified recipe has excellent organoleptic properties and is in high consumer demand.

During the research, the following changes were introduced to the basic recipe (analogue) in order to improve it:

– oat flakes were replaced with buckwheat, rice, and amaranth flakes;
– raisins were replaced with alternative freeze-dried fruits and berries;
– walnut kernels were replaced with almonds and hazelnuts;
– honey was replaced with maple syrup or Jerusalem artichoke syrup.

The replacement of honey with plant-based syrups was carried out taking into account the need to maintain an equivalent level of sweetness in granola compared to the selected analogue. It is known that the sugar content in 100 g of the product is as follows: honey – 80 g, Jerusalem artichoke syrup – 60.3 g, maple syrup – 68 g. Accordingly, the optimal amount of syrups was calculated to ensure the required level of sweetness.

The amount of sugar equivalent to 20 g of honey in 100 g of granola was determined using the formula (1.1)

$$M_{sug} = \frac{M_{hon} \cdot C_{hon}^{sug}}{100}, \tag{1.1}$$

where M_{sug} – mass of sugar in 100 g of granola provided by honey, g; M_{hon} – mass of honey according to the granola recipe, g; C_{hon}^{sug} – sugar content in 100 g of honey, g

$$M_{sug} = \frac{20 \cdot 80}{100} = 16g.$$

The required amount of syrups, which will provide 16 g of sugar in granola, was determined using the formula (1.2)

$$M_{syr} = \frac{M_{sug} \cdot 100}{C_{syr}^{sug}}, \tag{1.2}$$

where M_{syr} – mass of syrup, g; C_{syr}^{sug} – sugar content in 100 g of syrup: maple syrup – 68 g, Jerusalem artichoke syrup – 60.3 g, respectively:

$$M_{syr}^{marple} = \frac{16 \cdot 100}{68} = 23.5\,g,$$

$$M_{syr}^{Jerusalem\ artichoke} = \frac{16 \cdot 100}{60.3} = 26.5\,g.$$

Thus, 23.5 g of maple syrup and 26.5 g of Jerusalem artichoke syrup will be introduced into the experimental recipes.

As part of the scientific experiment, twelve experimental recipes were developed: six recipes based on rice flakes (**Table 1.1**) and six recipes based on buckwheat flakes (**Table 1.2**).

Table 1.1 Recipe composition of experimental granola samples based on rice flake

No.	Name and ingredient content, g							
	Rice flakes	Amaranth flakes	Freeze-dried peach	Freeze-dried strawberry	Almond	Jerusalem artichoke syrup	Maple syrup	Butter
rf1	20	80	20	30	30	26.5	–	20.0
rf2	50	50	20	30	30	26.5	–	20.0
rf3	80	20	20	30	30	26.5	–	20.0
rf4	20	80	20	30	30	–	23.5	20.0
rf5	50	50	20	30	30	–	23.5	20.0
rf6	80	20	20	30	30	–	23.5	20.0

Table 1.2 Recipe composition of experimental granola samples based on buckwheat flakes

No.	Name and ingredient content, g							
	Buckwheat flakes	Amaranth flakes	Freeze-dried cherry	Freeze-dried fig	Hazelnut	Jerusalem artichoke syrup	Maple syrup	Butter
rf7	20	80	30	20	30	26.5	–	20.0
rf8	50	50	30	20	30	26.5	–	20.0
rf9	80	20	30	20	30	26.5	–	20.0
rf10	20	80	30	20	30	–	23.5	20.0
rf11	50	50	30	20	30	–	23.5	20.0
rf12	80	20	30	20	30	–	23.5	20.0

The experimental samples were produced on the basis of the Educational and Research Laboratory of Restaurant Production Technology of the National University of Life and Environmental Sciences of Ukraine (Kyiv) using the following technology: dry gluten-free ingredients were measured in the quantitative ratios specified in the recipe and then thoroughly mixed until fully combined; the nuts were ground in a blender, the husk was removed by sieving and mixed with the dry gluten-free base; the syrups (maple and Jerusalem artichoke) were heated to 45°C and melted butter was added to them to obtain a liquid base. Then the liquid and dry bases were

combined and thoroughly mixed until the ingredients began to bind together. The prepared semi-finished product was spread evenly on a baking tray and placed into a steam convection oven preheated to 160°C. Heat treatment lasted 30 minutes. The temperature-time regime of heat treatment was selected based on the technological specifics of granola preparation in restaurant production conditions, in particular to ensure even roasting, prevent sugar caramelization and preserve organoleptic properties. This regime is recommended in literary sources for grain mixtures containing cereals, nuts, dried fruits, and natural syrups [22].

Freeze-dried cherries, peaches, and figs were chopped into 5–6 mm cubes. Freeze-dried strawberry slices were cut into 10–12 mm pieces. After heat treatment, the granola was cooled, broken apart if clumped, and then thoroughly mixed with the prepared freeze-dried ingredients. The finished product was packed in 250 g bags.

The organoleptic properties of the finished product were assessed, and the calorie content and glycemic index were calculated using the methodologies described in the literature.

The energy value of the experimental samples was determined using a formula based on the fact that the main macronutrients (proteins, fats, and carbohydrates) have different calorie content. Fats contain the most energy (9 kcal/g), while proteins and carbohydrates provide 4 kcal and 3.75 kcal per 1 g, respectively. Hence, the formula (1.3) is as follows

$$E = 4\sum P + 9\sum F + 3.75\sum C, \tag{1.3}$$

where E – total energy value (kcal per 100 g of granola); P – protein content (g per 100 g of granola); F – fat content (g per 100 g of granola); C – carbohydrate content (g per 100 g of granola).

1.3 Organoleptic evaluation of granola samples

Organoleptic or tasting evaluation is a key stage in the development of new gluten-free granola recipes, since it is the consumer perception of the product that ultimately determines the product's market success. The primary goal of the tasting is to analyze the organoleptic properties, including taste, aroma, texture, visual appeal, and overall quality assessment.

Taste characteristics play a key role in how consumers perceive the finished product. The expert commission assesses the harmony and balance of taste, paying attention to the level of sweetness, sourness, saltiness, and possible bitter notes.

Aroma is equally important and it should match the natural profile of the ingredients, be pleasant and be free from off-flavors that may appear due to improper storage or the use of low-quality raw materials.

The texture of granola is another important parameter in tasting evaluation. The product should not be too hard or too soft. Typically, granola has a crisp texture that should remain firm even after contact with milk or other liquids. During testing, experts analyze crispness retention and moisture absorption rate.

Visual appeal significantly influences consumer choice. Experts assess the uniformity of shape, color, and particle size of the product. A well-presented product directly affects its attractiveness to the end consumer and determines its competitiveness.

During the development of the recipe, it is necessary to establish the optimal ratio of the main components of the product, such as grain components, nuts, and freeze-dried fruits. Tasting analysis allows to determine the balance of these ingredients, ensuring a harmonious taste profile without the dominance of individual components.

An equally important factor is the ratio of sweeteners to other components of granola. Excessive or insufficient sweetness can significantly affect the final perception of the product.

To conduct a tasting assessment, quality criteria and their characteristics, which the finished product must meet, were developed (**Table 1.3**).

Table 1.3 Organoleptic quality indicators of gluten-free granola

Name of indicator	Its characteristics
Appearance	The shape of elements is without clear contours, their surface is not uniform with air pockets and particles of flakes of the certain crop, pieces of nuts, freeze-dried fruits, and berries
Taste and smell	The smell is pleasant, inherent in nuts, freeze-dried fruits, and berries; the taste is rich in nuts and freeze-dried fruits
Color	The rice-amaranth base is golden-brown. The buckwheat-amaranth base is light brown
Consistency	Dried, with large particles of raw materials mixed and bonded together

The five-point evaluation scale was applied, adhering to the following gradation: "excellent level" – 4.8...5.0 points, "good level" – 4.0...4.7 points, "satisfactory level" – 3.0...3.9 points, "low level" (marginally acceptable) – 2.0...2.9 points, "unacceptable level" – below 2.0 points. Granola samples scoring below 2.0 points were excluded from further research. To unify the evaluation of sensory properties, a detailed characteristic of each score was developed, which is presented in **Table 1.4**.

Table 1.4 Criteria for scoring sensory evaluation of gluten-free granola

Points	Criteria description
4.8...5.0 "excellent level"	Uniform, aesthetically appealing appearance, without burnt or stuck parts; intense, pronounced aroma (nuts, fruits, berries); rich, harmonious taste without off-flavors; ideal crispness and textural uniformity; golden-brown uniform color; components are well distributed
4.0...4.7 "good level"	Minor defects in appearance or color; pleasant but less intense aroma; good taste, with possible slight imbalance; almost crispy texture with minor deviations; slight unevenness in color or distribution of ingredients
3.0...3.9 "satisfactory level"	Noticeable irregularity in shape, partial sticking or burning; weakly expressed or insufficiently typical aroma; mediocre taste with indistinct or foreign notes; the texture is not crispy enough or with hard inclusions; uneven coloring
2.0...2.9 "low level"	Significant defects in appearance (sticking, burnt parts); unclear or weak aroma; undesirable or unbalanced taste; unacceptable texture: too hard or sticky; spotty or uneven color
below 2.0 "unacceptable level"	Pronounced defects in shape, color and structure; absence or unpleasant smell; strongly undesirable taste (bitterness, acidity, foreign flavors); texture is completely unacceptable for consumption; overall characteristics do not meet quality requirements

Average tasting scores are visualized in the form of quality profiles (**Fig. 1.1–1.4**).

In the process of analyzing the results of experimental studies presented in profiles (**Fig. 1.1–1.3**), it was found that all granola samples developed in accordance with the proposed recipe compositions received high tasting scores within the "good level" and "excellent level".

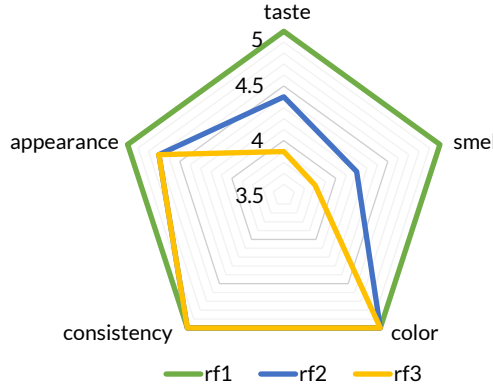

Fig. 1.1 Quality profiles of experimental gluten-free granola recipes based on rice and amaranth flakes and Jerusalem artichoke syrup

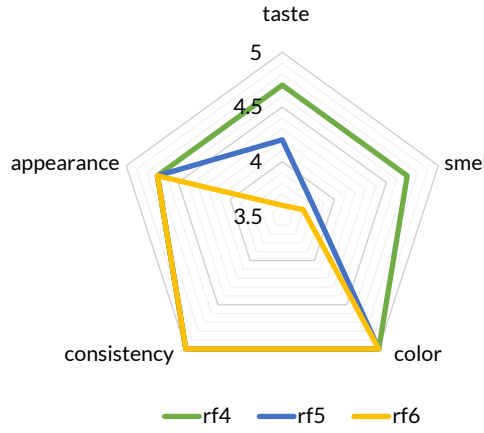

Fig. 1.2 Quality profiles of experimental gluten-free granola recipes based on rice and amaranth flakes and maple syrup

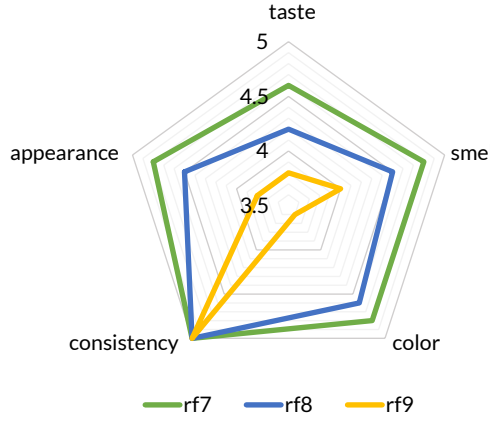

Fig. 1.3 Quality profiles of experimental gluten-free granola recipes based on buckwheat and amaranth flakes and Jerusalem artichoke syrup

The lowest average scores were recorded for granola samples that contained the maximum amount of buckwheat flakes (80%). In particular, the average score for the rf9 recipe composition with Jerusalem artichoke syrup was 4.03 points, and rf12, which contained maple syrup, received 4.08 points.

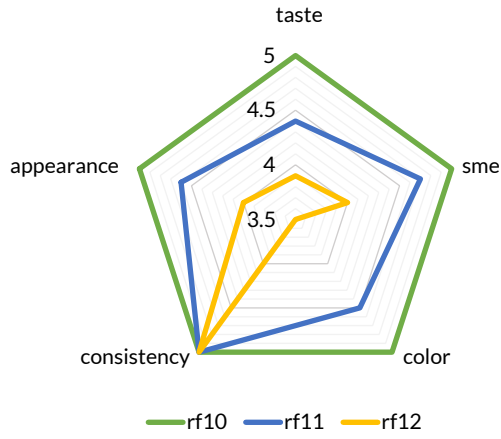

Fig. 1.4 Quality profiles of experimental gluten-free granola recipes based on buckwheat and amaranth flakes and maple syrup

The main criteria that caused the decrease in ratings were the taste and aroma characteristics, color and overall appearance of the product. Most tasters noted an imbalance in taste and aroma in the experimental samples with a high content of buckwheat flakes, which led to an excessive dominance of specific buckwheat notes. In addition, a significant proportion of buckwheat flakes in the composition led to the formation of a dark brown color with a grayish tint, which negatively affected the visual appeal of the product.

The reduction in the proportion of buckwheat flakes, accompanied by an increase in the amaranth content, had a positive effect on organoleptic properties, such as taste, aroma, color, and appearance. Granola samples containing 80% amaranth flakes and 20% buckwheat flakes received the highest tasting scores. Along with this, the use of maple syrup contributed to the harmonization of flavor characteristics, providing the most balanced combination of ingredients. Consequently, rf10 recipe received the highest average score of 5.0 points, while a similar rf7 recipe, but with Jerusalem artichoke syrup, was rated at 4.8 points.

A similar trend was observed in the organoleptic properties of granola produced on the basis of rice and amaranth flakes. The dominant rice taste and aroma in samples containing 80% rice flakes caused a decrease in the tasting scores, regardless of the type of syrup used. Thus, the average score of the rf3 recipe composition was 4.48, and the rf6 – 4.4 points. The decrease in the proportion of rice flakes in the recipe was accompanied by an increase in the overall product rating.

It is worth noting that all granola samples based on rice flakes had excellent color characteristics, as confirmed by consistently high tasting scores (5.0) for all recipes (rf1–rf6). The best result among this group of samples was achieved by granola containing 20% rice flakes and 80% amaranth flakes, with the use of Jerusalem artichoke syrup.

Thus, according to the results of the organoleptic evaluation, the most technologically feasible and sensory acceptable recipe is as follows: rf10, which contains 20% buckwheat flakes, 80% amaranth flakes, freeze-dried cherry and fig, crushed hazelnut kernels, butter, and maple syrup, and rf1, which includes 20% rice flakes, 80% amaranth flakes, freeze-dried peach and strawberry, crushed almond kernels, butter, and Jerusalem artichoke syrup.

The obtained results reveal a significant influence of the recipe composition on the organoleptic properties of granola and confirm the importance of the rational selection of components to achieve the optimal balance of taste, aroma, texture, and appearance of the finished product.

1.4 Energy value of gluten-free granola

The energy value of food products refers to the amount of energy the body receives as a result of their consumption. The body uses this energy to ensure all life processes, including physical activity, metabolism, organ function, and body temperature regulation.

Energy value is a crucial factor for consumers, as it affects the overall health, physical fitness, and prevents the development of various diseases. Knowledge of the energy value of products allows consumers to choose food that best meets their needs and ensures a proper a balance between energy intake and expenditure.

The energy value of food products, including gluten-free granola, is determined per 100 g of the edible potion of the finished dish using formula (1.3).

The initial data for calculating the energy value of the experimental granola recipes are presented in **Table 1.5**.

The total amount of each macronutrient for a certain recipe was determined by formula (1.4)

$$C_{rfi}^{mac} = \sum_{i=1}^{n} mac_i, \tag{1.4}$$

where C_{rfi}^{mac} – the amount of macronutrient in the experimental sample produced according to *i*-th recipe, g; mac_i – the content of macronutrient in a certain ingredient of the recipe, g; n – the number of ingredients in the recipe.

The content of each macronutrient in the experimental granola recipes was calculated by formula (1.5)

$$mac_i = \frac{M_i^p \cdot C_{mac}^{100}}{100}, \quad (1.5)$$

where, M_i^p – the amount of certain ingredient in the recipe, g; C_{mac}^{100} – the content of macronutrient in 100 g of a certain ingredient in the recipe, g.

Results of the calculation of the total content of macronutrients in the experimental granola recipes are given in **Table 1.6**.

The results of determining the energy value (formula (1.3)) of gluten-free granola, which is produced according to the developed experimental recipe compositions, are given in **Table 1.7**.

Table 1.5 Initial data for calculating the energy value of gluten-free granola

Name of ingredient	Content of macronutrients, g per 100 g		
	proteins	fats	carbohydrates
Amaranth flakes	16.00	7.00	65.00
Buckwheat flakes	16.52	2.43	76.61
Rice flakes	6.61	0.50	77.00
Butter	1.00	82.3	0.80
Jerusalem artichoke syrup	0.50	0.00	75.00
Maple syrup	0.20	0.00	68.02
Freeze-dried cherry	1.10	0.51	80.11
Freeze-dried peach	3.04	0.01	68.52
Freeze-dried fig	5.05	1.00	85.19
Freeze-dried strawberry	1.00	0.30	85.00
Almond kernels	18.60	57.70	16.20
Hazelnut kernels	16.10	66.90	9.92
Oat flakes	13.00	6.50	60.00
Raisins	3.10	0.30	79.30
Walnuts	15.20	65.20	13.70
Honey	0.30	0.00	82.40

Table 1.6 Results of calculation of the total macronutrient content in the experimental granola recipes

Recipe number	Granola output, g	Macronutrient content, g per 100 g		
		proteins	fats	carbohydrates
Industrial analogue (control)	250.0	26.35	75.21	57.39
rf1	250.0	21.13	39.47	129.85
rf2	250.0	18.31	37.52	133.45
rf3	250.0	15.49	35.57	137.05
rf4	250.0	21.05	39.47	125.98
rf5	250.0	18.23	37.52	129.58
rf6	250.0	15.41	35.57	133.18
rf7	250.0	22.60	42.91	131.33
rf8	250.0	22.75	41.54	134.81
rf9	250.0	22.91	40.16	138.29
rf10	250.0	22.51	42.91	127.47
rf11	250.0	22.67	41.54	130.95
rf12	250.0	22.82	40.16	134.43

Table 1.7 Results of calculating the energy value of gluten-free granola

Recipe number	Mass of the experimental sample, g	*E*, kcal per mass of the experimental sample	*E*, kcal per 100 g of mass
Industrial analogue (control)	250.0	997.50	399.00
rf1	250.0	926.68	370.67
rf2	250.0	911.35	364.54
rf3	250.0	896.02	358.41
rf4	250.0	911.86	364.74
rf5	250.0	896.53	358.61
rf6	250.0	881.20	352.48
rf7	250.0	969.02	387.61
rf8	250.0	970,36	388.15
rf9	250.0	971.71	388.68
rf10	250.0	954.19	381.68
rf11	250.0	955,54	382.22
rf12	250.0	956.89	382.76

Analysis of the data presented in **Table 1.7** reveals that the energy value of all developed experimental granola variants per 100 g is nearly identical and ranges within 352...389 kcal/100 g.

Recipes containing buckwheat flakes have maximal energy values, while rice-based granola variants have slightly lower values. However, this difference is not significant.

The energy value of the control granola sample (industrial analogue) exceeded the highest value among the experimental variants by 10 kcal and amounted to 399 kcal.

According to nutritional standards, the recommended energy value of breakfast is 300...400 kcal. Therefore, both the control and experimental gluten-free granola recipes comply with these standards.

1.5 Glycemic index of gluten-free granola

One of the key parameters to consider when developing new breakfast cereal recipes is the glycemic index (GI). This index characterizes the rate and extent of blood glucose level increase after consuming a particular food product.

Food products with a high GI (over 70) cause a sharp increase in glucose levels, which may be undesirable for people at risk of developing diabetes or those already diagnosed with the condition. A sharp rise in glucose concentration stimulates active insulin production, which, in turn, may contribute to the development of insulin resistance and overall deterioration of health. Therefore, when creating breakfast cereals, it is advisable to use ingredients with a low or medium GI (below 55), as they help to maintain stable blood glucose levels and are especially beneficial for people with metabolic disorders.

In addition, low-GI food products provide a long-lasting feeling of satiety due to the gradual release of glucose into the bloodstream. This plays a crucial role in appetite control and body weight regulation. Consuming low-GI breakfast cereals helps to prevent sudden fluctuations in glucose levels, which can lead to rapid hunger and excessive snacking. The glycemic index of individual ingredients used in the experimental recipe compositions is given in **Table 1.8**.

Table 1.8 Glycemic index (GI) of gluten-free granola ingredients

Ingredient name	GI of ingredients, r.u. per 100 g
1	2
Amaranth flakes	35.0
Buckwheat flakes	40.0

Continuation of Table 1.8

1	2
Rice flakes	80.0
Butter	15.0
Jerusalem artichoke syrup	13.0
Maple syrup	54.0
Freeze-dried cherries	30.0
Freeze-dried peach	35.0
Freeze-dried fig	50.0
Freeze-dried strawberry	30.0
Almond kernels	25.0
Hazelnut kernels	15.0
Oat flakes	55.0
Raisins	64.0
Walnuts	15.0
Honey	65.0

Calculation results. The results of determining the glycemic index of the developed gluten-free granola recipe compositions are visualized in **Fig. 1.5**.

The glycemic index value for a certain recipe was determined by formula (1.6)

$$GI_{rfi} = \sum_{i=1}^{n} GI_i, \tag{1.6}$$

where GI_{rfi} – glycemic index of the experimental sample, prepared according to the i-th recipe, r.u.; GI_i – glycemic index of a specific ingredient in the recipe, r.u.; n – number of ingredients in the recipe.

The glycemic index of each individual ingredient in the experimental granola recipes was calculated according to formula (1.7)

$$GI_i = \frac{M_i^p \cdot GI^{100}}{100}, \tag{1.7}$$

where M_i^p – recipe amount of a specific ingredient, g; GI^{100} – glycemic index of 100 g of a specific ingredient of the recipe, r.u.

Calculation results determining the glycemic index of the developed gluten-free granola recipe compositions are visualized in **Fig. 1.5**.

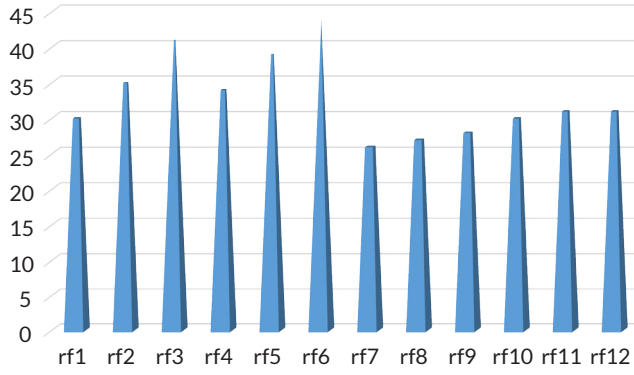

Fig. 1.5 Glycemic index of experimental granola recipe compositions

The control sample (**Fig. 1.5**) is characterized by a glycemic index (GI) of 41, which corresponds to the upper limit of the medium GI range. This value is typical for traditional granola, which includes oat flakes, raisins, and honey – ingredients high in simple carbohydrates, which are quickly absorbed by the body. Analysis of the experimental samples (rf1–rf12) showed a decrease in glycemic index in most variants compared to the control, except for samples rf3 and rf6. In particular, the GI of sample rf6 was 44, which exceeded this indicator in the control variant and was associated with the highest content of rice flakes in the recipe. At the same time, the lowest GI values were observed in samples rf7, rf8, and rf9, indicating the potential advantage of these recipes for dietary nutrition and for developing products with a moderate impact on the body's glycemic response.

1.6 Discussion of results

The research aimed to develop a recipe and improve the production technology of gluten-free granola for the restaurant segment.

The working hypothesis of the research was to develop a granola recipe composition based on gluten-free grain ingredients, freeze-dried fruit and berry raw materials, and nuts. It should also be noted that traditional granola production methods typically use honey as a natural sweetener. However, heat treatment of honey at 160°C or higher temperatures can lead to the formation of harmful compounds, in particular carcinogens, which are associated with an increased risk of cancer. To minimize these negative consequences, let's propose modifying the technological

process by replacing honey with alternative sweeteners, in particular, maple syrup and Jerusalem artichoke syrup.

Amaranth flakes, selected as the main ingredient, are considered a valuable product for healthy nutrition. In 100 grams of these flakes, there are 16 g of protein, 3 g of minerals, and 17 mg of vitamins. A significant advantage is their high content of lysine and other essential amino acids, which cereal crops typically lack. Amaranth flakes also contain healthy fats (7 g per 100 g), including polyunsaturated fatty acids. The starch content in amaranth flakes reaches 7 g per 100 g, making them a good source of complex carbohydrates that provide sustained energy. In amaranth, starch is also highly soluble and digestible, which facilitates easier digestion. A fairly high fiber content (8 g per 100 g) helps normalize digestion. A rich mineral composition of amaranth classifies it as an exceptionally nutritious food that supports healthy eating, particularly for individuals with increased micronutrient needs. Squalene (6.1 g), a powerful antioxidant found in amaranth, has anti-inflammatory and immunomodulatory properties. Amaranth flakes are gluten-free, making them suitable for individuals with gluten intolerance.

Buckwheat flakes contain all the essential amino acids, making them an important source of protein. They are a source of complex carbohydrates, which promote long-lasting satiety and help maintain stable blood sugar levels. Their high dietary fiber content helps to improve digestion, normalize bowel function, and promote detoxification. They contain a small amount of fat, including beneficial polyunsaturated fatty acids – linoleic and linolenic – as well as Omega-3 and Omega-6.

The main portion of carbohydrates in rice flakes consists of complex carbohydrates that ensure gradual energy release. Rice flakes contain a small amount of protein, which is less complete, compared to animal proteins, due to the absence of the essential amino acid lysine. The fat content is low, and it mostly consists of unsaturated fatty acids. Rice flakes contain little fiber. They are gluten-free, making them safe for people with celiac disease or gluten intolerance. Due to their high carbohydrate content, rice flakes are an excellent source of quick energy. They are easily digestible, making them suitable for individuals with sensitive digestive systems or during dietary nutrition.

Jerusalem artichoke syrup is known for its beneficial properties thanks to its high inulin content (40 g per 100 g), a natural prebiotic. It is used as a sugar substitute due to its low glycemic index. Maple syrup can be a better alternative to regular sugar due to its more natural composition and beneficial micronutrients, though it should still be consumed in moderation because of its high carbohydrate content.

An important group of granola ingredients consists of non-cereal plant-based components. These include freeze-dried cherry, peach, and fig fruits, as well as strawberry berries. All freeze-dried products retain most of the beneficial nutrients found in fresh fruits.

The results of organoleptic evaluation demonstrated a significant impact of the recipe composition on the consumer properties of the finished product. It was found that a balanced combination of gluten-free flakes (buckwheat, rice, amaranth), freeze-dried fruits and berries, and nuts is crucial for achieving high sensory characteristics. Thus, the samples with a high content of buckwheat flakes received lower ratings due to the dominance of a specific buckwheat flavor and less appealing color. In contrast, increasing the proportion of amaranth flakes had a positive effect on organoleptic qualities, improving the taste, aroma, and visual appeal of the granola.

The replacement of honey with maple syrup and Jerusalem artichoke syrup was a key aspect of the study. The results indicated that the use of maple syrup contributed to better flavor harmony in granola based on buckwheat and amaranth flakes, while Jerusalem artichoke syrup proved to be a suitable sweetener for the recipe with rice and amaranth flakes.

The calculation of energy value showed that all developed recipes fall within the acceptable range for breakfast (352–389 kcal/100 g), which complies with recommended dietary norms. At the same time, granola based on buckwheat flakes had a slightly higher energy value compared to the rice-based one. However, the highest energy value was characteristic of the control sample (commercial analogue).

The results obtained indicate a clear and predictable dependence of the glycemic index (GI) of the experimental granola recipes on the composition of their components.

All ingredients used in the developed recipes belong to the category of low-GI products, except for maple syrup (medium GI) and rice flakes (high GI). Consequently, recipe compositions, which used Jerusalem artichoke syrup as a sweetener, exhibited a lower glycemic index compared to those containing maple syrup. Among the buckwheat-based recipes, the lowest GI was observed in composition rf7, which contained Jerusalem artichoke syrup and a minimal amount of buckwheat flakes.

Rice-based recipe compositions had a higher glycemic index compared to buckwheat-based ones, which is attributed to the high GI of rice flakes. Correlation analysis confirmed a strong direct dependence between the content of rice flakes and the glycemic index of the finished product, with a correlation coefficient of 0.92. The lowest GI value among the recipes of this group was demonstrated by the composition rf1, which contained a minimal amount of rice flakes, Jerusalem artichoke syrup, and other components.

It is important to note that despite some variations in the glycemic index values, all the experimental granola samples fall into the category of low-GI products (below 55 units). This indicates their suitability for inclusion in the diet of individuals with diabetes and those who follow a dietary nutrition plan.

The studies conducted by the authors correlate with those carried out by I. Kaluhina [2], S. Langyan [6] regarding the use of pseudocereal crops, as well as by M. Montenegro [14], and A. Saraiva [12] concerning the use of syrups in granola production.

Summarizing the findings of experimental studies, it can be concluded that in terms of organoleptic properties, energy value, and glycemic index, the most promising granola recipes are as follows: rf10 containing buckwheat and amaranth flakes, freeze-dried cherries and figs, crushed hazelnut kernels and maple syrup, and rf1 containing a minimal amount of rice flakes combined with amaranth flakes, freeze-dried peach, freeze-dried strawberry, almond kernels, and Jerusalem artichoke syrup.

These recipes can be recommended for implementation in production in the restaurant segment.

Technological schemes were developed for the production of gluten-free granola in the restaurant segment based on recipe compositions that were recognized as the best according to the results of experimental studies (**Fig. 1.6, 1.7**).

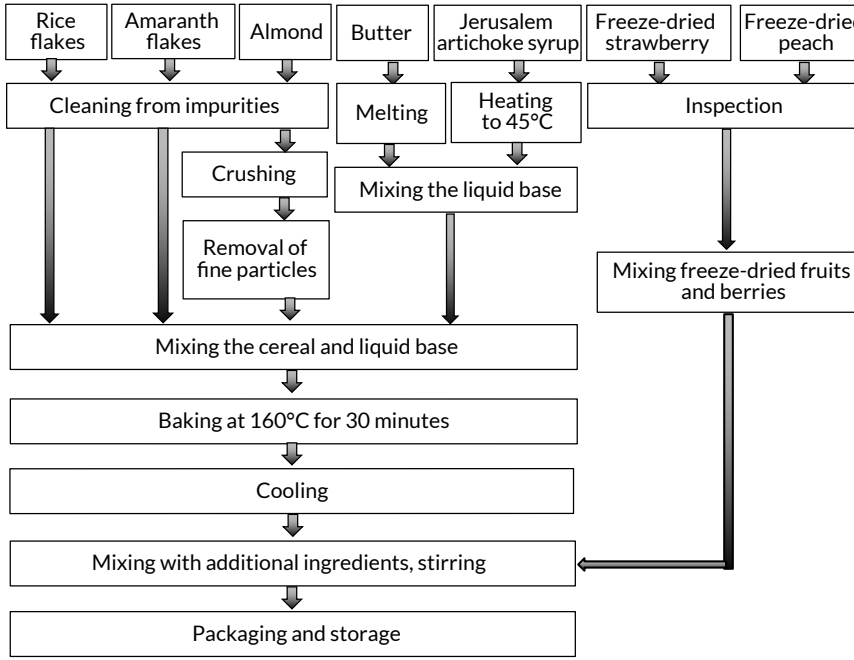

Fig. 1.6 Technological flowchart for the production of gluten-free granola based on the experimental recipe rf1

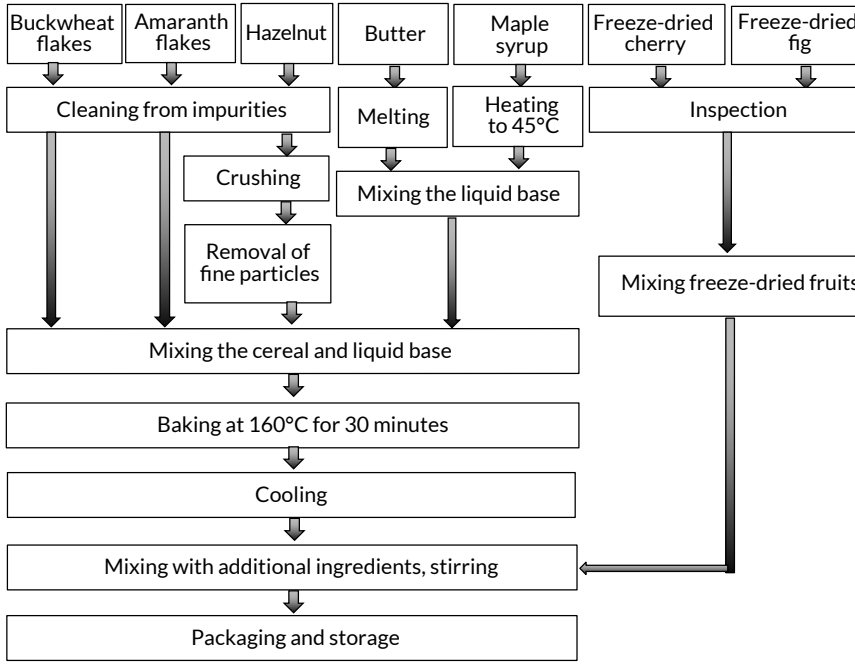

Fig. 1.7 Technological scheme for the production of gluten-free granola based on the experimental recipe rf10

The improved granola production technology differs from the traditional one by incorporating plant-based ingredients with improved functional characteristics into the recipe, as well as implementing additional preparation stages before production.

The production cost of 1 kg of granola using the traditional technology (industrial analog) amounts to 8.81 EUR. In experimental samples, the use of freeze-dried fruits and berries and other high-cost components, such as amaranth flakes, premium nuts, and functional syrups, increases the cost of granola to 15.31 EUR for rf10 recipe and 17.55 EUR for rf1 recipe.

Despite the higher production cost, the experimental granola samples demonstrate economic viability due to the introduction of innovative raw materials and premium product positioning. Specifically, the sale of gluten-free granola produced using buckwheat and amaranth flakes, maple syrup, butter, hazelnut kernels, and freeze-dried cherries and figs (rf10 sample) makes a profit of 3745.61 EUR per ton of product, so that the level of profitability comprises 25%. Meanwhile, the profit

from selling granola based on rice and amaranth flakes with Jerusalem artichoke syrup, butter, almond kernels, and freeze-dried peaches and strawberries (rf1 sample) amounts to 1501.86 EUR per ton under 9% profitability.

Future research could focus on studying the impact of different heat treatment regimens on the quality and safety of gluten-free granola using alternative sweeteners, as well as investigating shelf life and packaging materials to preserve the organoleptic and physicochemical properties of the finished product. Additionally, expanding the range of gluten-free granola by incorporating other types of gluten-free flakes, freeze-dried vegetables, and seeds can be an interesting direction.

The research findings significantly contribute to developing innovative food products for the restaurant industry, particularly in the gluten-free nutrition segment. They can also promote expanding a range of healthy and safe breakfast options for consumers.

1.7 Conclusions

Twelve gluten-free granola recipe compositions were developed for scientific research.

The study confirmed that the energy value of all proposed granola recipes per 100 g is nearly identical, ranging within 352...389 kcal/100 g, which aligns with the established nutritional standards. Recipes containing buckwheat flakes exhibited a higher energy value, while rice-based granola had a slightly lower energy value. However, this difference is not significant.

The results confirm a direct and predictable significant dependence of the glycemic index (GI) of the experimental granola recipes on the ingredient composition. According to the research results, despite minor variations in GI values, all developed recipes belong to the group of products with a low glycemic index (below 55 units). This makes them suitable for individuals with diabetes, as well as for inclusion in dietary nutrition.

It was established that from the perspective of organoleptic properties, energy value, and glycemic index, two granola recipes are the most promising: rf10 containing buckwheat and amaranth flakes, freeze-dried cherry and fig, crushed hazelnut kernels, and maple syrup, and rf1 containing a minimal amount of rice flakes combined with amaranth flakes, freeze-dried peach and strawberry, almond kernels, and Jerusalem artichoke syrup.

As a research result, the technology for producing gluten-free granola was improved by incorporating plant-based ingredients with improved functional

characteristics into the recipe, as well as implementing additional preparation stages before production. This improvement contributes to increasing nutritional value, improving organoleptic properties, and expanding the range of functional food products that meet modern requirements for healthy nutrition.

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CHAPTER 2

A multi-criteria strategy for assessing the quality of frozen raw cherry fruits

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Olga Pyurko
Yana Mulienok

Abstract

The optimization of the food chains, in particular the storage and processing of raw materials into final products, is becoming a particularly difficult task for the regions which face humanitarian crises, protracted political conflicts and natural disasters. Cherries are one of the most popular fruits in the confectionary industry used. Freezing is one of the most effective methods of long-term preservation of cherries. At the same time, frozen raw materials, like any other product, can undergo changes that negatively affect the quality of the final product. This may include deterioration of taste characteristics, loss of vitamins, and risk of developing microbiological processes in case of the violation of storage or transportation conditions. In this context, the implementation of comprehensive assessment of the cherry fruits quality becomes especially relevant. Therefore, systematic monitoring of physical, biochemical and sensory parameters is necessary to obtain high-quality frozen raw materials. A method of multi-criteria evaluation of frozen fruit was proposed. The objective functions were calculated and a ranking series of the suitability of the frozen fruits for the production of candied fruit was formed. By using a multi-criteria optimization method, the most suitable cherry cultivars for freezing were determined. A scientifically based complex of quality parameters of functional technological indicators of frozen fruit is presented. The selection of the optimal cultivar of fruit raw materials with high quality indicators and minimal losses was carried out by means of a comparative evaluation of the cultivars according to their properties using a multi-criteria method based on a geometric convolution of criteria. Chemical, physical and

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organoleptic criteria of frozen semi-finished products may change depending on the varietal characteristics of cherries. Therefore, choosing the optimal cultivar requires a comprehensive approach. The use of a multi-criteria optimization method made it possible to establish relationships between the quality characteristics of the fruits and their permissible values. This made it possible to determine the fruit of Griot Melitopol cultivar as the best frozen raw material according to functional, technological and sensory indicators. This can further be used to improve criteria for evaluating the quality of frozen fruit pulp within a zero-waste fruit supply chain, ensuring efficiency and sustainable use of resources for all stakeholders.

Keywords

Fruit, amount of juice loss, sensory analysis, biochemical indicators, freezing, storage, geometric convolution criteria.

2.1 Introduction

Today's global food system remains vulnerable and unstable. The consequences of Russian aggression on the territory of Ukraine have deepened the negative trends in the global food sector. The food system covers all stages from the production of food to the consumption of ready-made food. An important chain of the food system is storage and processing of raw materials into a final product [1]. Food industry, in particular the processing of fruit raw materials, is an integral part of a food system and an important lever for the transformation of value chains in the context of achieving sustainable development goals [2].

In modern conditions of increased requirements for the quality of food products, ensuring the stability of the technological characteristics of semi-finished products is of particular importance. Frozen fruit raw material, in particular cherries, is widely used in the production of confectionary and candied products, yogurt and other food products and their quality directly affects the consumer properties of the final products, the economic efficiency of production and the competitiveness of the enterprises in the processing industry. A modern strategy for the processing of fruit raw materials requires the implementation of innovative approaches to the preparation and selection of raw materials for production [3].

A modern strategy for the processing of fruit raw materials requires the implementation of innovative approaches to the preparation and selection of raw materials for production [4]. High competition among stakeholders stimulates them to constantly improve not only the range of products, but also the technological processes of preparing semi-finished products. According to literature reviews, there is

growing interest in the extended period of the use of fruit raw materials, in particular, in the practice of fruits pre-freezing. This approach is important because freezing allows to significantly extend the storage life of fruit raw materials, which makes it possible to ensure a continuous process of raw material processing throughout a year, despite the seasonality of fruit harvesting [5, 6]. The use of frozen fruit in the food industry allows to for efficient processing of fruit that requires a quick marketing solution to reduce spoilage and minimize wastage. This approach allows to integrate fruits of different degrees of ripeness and commercial grade into a zero-waste processing chain. Delayed processing of fruits for further use is possible if they are previously frozen [7].

The suitability of fruits of different cultivars for freezing is assessed on the basis of physical, technological and sensory characteristics. Frozen candied fruits for further use must meet a number of quality requirements: organoleptic parameters (taste, smell, color), physicochemical properties (solids content, acidity, degree of freezing) and safety parameters (absence of pollution, pesticide residues, etc.). In addition, the technological properties of raw material are important, in particular, its ability to retain its shape, color and texture after the processes of defrosting and sugaring [8, 9].

One of the main problems affecting the quality of fruit raw material is the deterioration of its properties during freezing and storage. In the process of freezing, damage to the cellular structure of fruit can occur due to the formation of large ice crystals, which leads to the loss of cell juice during defrosting, changes in texture, darkening of color and reduction of aroma. The intensity of these changes depends on a number of factors, in particular the cultivar and varietal characteristics of raw material.

Cherry is a valuable fruit raw material for the processing industry due to its sensory properties and the presence of components important for full nutrition. It contains organic acids (from 0.7 to 3.0%), sugars (from 6.5 to 21.5%), as well as vitamin C (from 13 to 19 mg/100 g of product weight). Freezing is one of the most effective methods of a long-term storage of fruits, in particular, of cherries. Studies of the suitability of different cultivars of cherries for freezing were conducted by both Ukrainian and European scientists. Experimental studies made it possible to draw conclusions about the suitability of certain cherry cultivars for freezing as well as to determine the optimal storage period for these fruits [10, 11].

The quality of frozen cherry raw materials for further use depends on several factors, such as a cultivar, stage of ripeness, pre-treatment and duration of storage in the freezer. The choice of cherry cultivars is critically important, as they are characterized by different physical and chemical parameters [12, 13]. This significantly affects the quality of the final product.

The relevance of quality control of frozen cherry raw materials for further use is due to the need to ensure the stability of the final product parameters. Control of organoleptic, physico-chemical and microbiological indicators not only prevents the production of low-quality finished products, but also guarantees the safety for consumers. Therefore, proper control at all stages of storage and processing of frozen cherries is a key element of an effective production process that ensures high quality of semi-frozen products [7].

Food products are polydisperse systems, which differ in various physical properties and composition of biochemical components. One of the main factors determining the quality of a fruit product of fruit origin is the composition of raw material to be processed. Therefore, frozen fruit products require additional research on functional and technological indicators to select optimal cultivars, that are suitable for further use of raw materials [14].

However, the analysis of each quality indicator separately does not allow to form a set of parameters that determine the best cultivar. Therefore, in order to choose the optimal cultivar of fruits that can be recommended for further of use semi-finished products, it is necessary to use a comprehensive assessment. One of the modeling methods based on complex quality indicators is the generalized desirability function proposed by Harrington. This function is based on the transformation of the natural values of individual indicators (feedback) into a dimensionless scale reflecting desirability or preference [15]. In scientific studies, it was used to determine minimal product losses and optimal methods of fruit freezing. This made it possible to summarize quality indicators of frozen cherry fruits in different ways and determine the best variant [16]. The approach, based on the desirability function, was used for the optimization of extraction conditions of the antioxidant olive leaf compounds by means of water- alcohol solvent [17].

One of the methods of a comprehensive assessment of fruits based on a set of quality indicators is a method of multi-criteria optimization. This approach is based on taking into account the measurement units of quality indicators and values of the intervals of permissible values of each indicator when choosing the best cultivar of fruit for freezing [18].

In this regard, the task of developing an effective strategy for multi-criteria selection of frozen cherry raw material, which will allow to optimize the process of semi-finished products production and ensure high quality of the final product, arises. This approach involves taking into account a complex of parameters and applying methods of quantitative and qualitative analysis to make substantiated decisions. The relevance of this issue is increasing in the conditions of modern production, where the consumers make high demands for the products quality. Increased

attention to the technological processes of storage, processing and quality control of raw materials allows to minimize the risks of deterioration of the final product quality, which directly affects the reputation of the producer and the competitiveness of its product in the market.

The purpose of this section is to substantiate and develop a multi-criteria strategy for choosing frozen cherry raw material for further use of semi-finished products, aimed at achieving the highest quality of a final product. Special attention is paid to the assessment of key parameters of raw materials and the implementation of a systematic approach to decision-making at all stages of its selection.

2.2 Development of the methodology for selecting the best cherry cultivars suitable for freezing on the basis of criterion indicators

In the process of production of frozen semi-finished products, it is especially important to select a scientifically based cultivar. In Ukraine, cherry is one of the most popular fruits used for the production of frozen products. As mentioned earlier, each cherry cultivar has a unique biochemical, commodity and sensory characteristics. These functional and technological parameters determine the taste qualities of fruits after freezing and significantly affect their suitability for further processing.

The scientific substantiation of the selection of cultivars suitable for freezing was carried out using a modified method. The basis of this method is the use of decision-making mechanism based on several predefined criteria, which allows to eliminate the influence of measurement units and the interval values of permissible values of each criterion on a cultivar selection (objective function).

The selection of the most suitable cultivar for freezing was carried out by the method of multi-criteria optimization [18]. The selection criteria were determined by the main requirements for cherry fruits. The most important among them are the following: the fruits should be large in size, of a uniform intense red color, with a thin skin, dense pulp and a small stone. An important characteristic is a low tendency to browning, as well as an optimal ratio of organic acids and sugars (sugar-acid index). Cherry fruits should not have too sour taste.

In order to scientifically justify the selection of cherry fruits suitable for freezing, using the method of multi-criteria optimization, the following algorithm of the main stages was developed:

1. Formulation of the optimization task. At this stage, the main criteria and their significance for the final product were determined. As the main criteria A_j key

physico-chemical parameters and sensory evaluation of frozen cherry fruits were selected: amount of juice loss, % (A_1); content of dry soluble substances, % (A_2); sugar content, % (A_3); titrated acids content, % (A_4); total content of phenolic compounds (A_5); vitamin C content mg (A_6); general sensory evaluation of fruits (A_7).

2. Collection of experimental data. The research was conducted during 2007–2019. The objects of the research were fresh fruits of ten cherry cultivars. The line of experimental cultivars included: Ozhydanie (Early maturing period); Vstrecha, Shalunia, Siyanets Turovtsevoi, Griot Melitopolskiy, Modnytsia, Ekspromt (medium maturing period); Melitopolska Purpurna, Solidarnist, Igrushka (late maturing period).

Cherry fruits for further freezing were collected at the consumer stage of ripeness. The fruits were sorted, inspected, washed and frozen loosely in a freezer in a slow way. The freezing temperature was minus 24 ± 1°C until the internal temperature of the fruit was minus 18°C. After that, they were packed in polyethylene film bags of 0.5 kg each and stored for three months at a temperature of minus 18°C. Determination of the components of the chemical composition, technological and organoleptic indicators were performed three times in fresh fruits on the day of collection: in fresh frozen fruits, in frozen fruits after 1 and after 13 months of storage.

All measurements were performed according to standard methods [18]:

– **the amount of cell juice loss** – by determining the difference of fruit weight before and after defrosting;

– **the content of dry soluble substances** was determined using a refractometer.

The method is based on determination of the mass fraction of dry soluble substances by the refractive index. The refractive index of the analyzed solution was measured at a temperature of (20.0 ± 0.5°C) on the ABBE AR12;

– **the mass concentration of sugars** was determined by the ferricyanide method. This method is based on the ability of reducing monosaccharides to reduce potassium ferricyanide K3[Fe(CN)6] (red blood salt) in ferric blue (ferrocyanide) potassium K4[Fe(CN)6] (yellow blood salt) in an alkaline medium. Methylene blue was used as an indicator. When reducing potassium ferricyanide, a change in the color of the solution from blue to colorless or light yellow was observed. The amount of sucrose was determined by previously converting it to invert sugar;

– **the content of titrated acids** was determined by the titrimetric method. The method consists in the neutralization of organic acids contained in the studied product with the help of 0.1 alkali solution. Titration is carried out until the moment of transition of the solution from an acidic environment to an alkaline one. This transition is recorded visually by the appearance of a pink color of the solution in the presence of the phenolphthalein indicator. The accuracy of the method is ± 0.5%;

– **the content of phenolic substances** was determined using the Folin-Denis reagent. The method is based on the complexation reaction of polyphenols with the Folin-Denis reagent, which results in the formation of colored compounds that allow to determine the optical density. The rutin standard was used to calculate the content of polyphenols in cherry fruits;

– **the content of ascorbic acid** was determined by the iodometric method using the Tillmans reagent. The method is based on the reducing properties of ascorbic acid. Under the influence of ascorbic acid, the solution of the indicator 2.6-dichlorophenolindophenol, which was a blue color, was reduced to a colorless compound.

The general sensory evaluation of frozen cherry fruits was carried out on a 9-point scale.

The obtained data will be analyzed below.

3. Normalization of criteria. This was done in order to eliminate the influence of units' measurement of physico-biochemical and sensory criteria of fruits of various cultivars, which allows to transit their values into dimensionless quantities ($f_j \to \widehat{f}_j$).

Before carrying out the normalization operation, it is necessary:

– to set the maximum (f_j^+) and minimum (f_j^-) values of j-criterion of the studied cultivars (x_i);

– the optimal value of j-criterion was determined according to the following rule:

a) if the evaluation criterion (f_j) tends to the minimum value, then

$(f_j^{opt} \to \min)$, then $f_j^{opt} = f_j^-$;

b) if the evaluation criterion (f_j) tends to the maximum value, then

$(f_j^{opt} \to \max)$, then $f_j^{opt} = f_j^+$.

The optimal value of j-criterion (f_j^{opt} min; f_j^{opt} max) is taken into account when choosing formula (2.1) for the normalization operation

$$\widehat{f}_j(x_i) = \begin{cases} \dfrac{(f_j(x_i) - f_j^-)}{(f_j^+ - f_j^-)}, \text{if } f_j^{opt} \to \max; \\ \dfrac{(f_j^+ - f_j(x_i))}{(f_j^+ - f_j^-)}, \text{if } f_j^{opt} \to \min, \end{cases} \tag{2.1}$$

where $\widehat{f}_j(x_i)$ – the value of j-criterion in the normalized form for the i-cultivar; $f_j(x_i)$ – the value of j-criterion for the i-cultivar in the corresponding units of measurement; $f_j^+; f_j^-$ – the area of permissible values of j-criterion of the compared cultivars.

4. Calculation of the values of the objective function. After the normalization operation, the values of the target function (*j*) were calculated for each cultivar (x_i) according to formula (2.2)

$$\varphi(x_i)=\sum^{n}\left|\widehat{f}_j(x_i)-\widehat{f}_j(x^i)\right|\to\min,\ \text{where}\ 0\le\widehat{f}_j(x_i)\le 1; \tag{2.2}$$

$$\widehat{f}_j\left(x^i\right)=1,$$

where $j(x_i)$ – a target function for the *i*-cultivar; *n* – number of criteria; $\widehat{f}_j\left(x_i\right)$ – value of *j*-criterion in a normalized form for the *i*-cultivar; $\widehat{f}_j\left(x^i\right)$ – value of *j*-criterion in a normalized form for the ideal cultivar; x^i – an ideal cultivar (with optimal criteria values).

Proof that $\widehat{f}_j\left(x^i\right)=1$.

If $f_j^{opt}\to\max$, then according to formula (2.2), the value of *j*-criterion in the normalized form for an ideal cultivar, can be calculated using formula (2.3)

$$\widehat{f}_j\left(x^i\right)=\frac{f_j\left(x^i\right)-f_j^-}{f_j^+-f_j^-},\ \text{as}\ f_j\left(x^i\right)=f_j^{opt}=f_j^+. \tag{2.3}$$

If $f_j^{opt}\to\min$, then according to formula (2.2) it is possible to calculate the value of *j*-criterion in normalized form for an ideal cultivar using formula (2.4)

$$\widehat{f}_j\left(x^i\right)=\frac{f_j^+-f_j\left(x^i\right)}{f_j^+-f_j^-},\ \text{as}\ f_j\left(x^i\right)=f_j^{opt}=f_j^-. \tag{2.4}$$

5. Analysis of the obtained results. The choice of the best cultivar is determined by the conditions of maximum approximation of its target function to the target function of an ideal cultivar, which is equal to 0.

Let's prove that $\varphi\left(x^i\right)=0$.

According to formula (2.5)

$$\varphi\left(x^i\right)=\sum^{n}\left|\widehat{f}_j\left(x^i\right)-\widehat{f}_j\left(x^i\right)\right|=\sum^{n}|1-1|=0. \tag{2.5}$$

Therefore, the smaller the value of the target function of the cultivar in the range of criteria values of the studied cultivars, the higher the suitability of the frozen raw material for the production of candied fruit. The construction of ranked series and the selection of the best cherry cultivar suitable for freezing in the range of criteria values is based on this principle.

2.3 Dynamics of juice loss in cherry fruits during freezing and further storage

One of the most important technological indicators characterizing the quality of frozen product is the amount of juice loss. It directly reflects the degree of structural damage to the cellular tissue of the fruit. Determining the amount of juice loss makes it possible to predict the behavior of cherry fruits cultivars in various technological processes. **Table 2.1** shows the results of influence of defrosting of frozen cherry fruit on the amount of juice loss.

Table 2.1 Amount of juice loss during defrosting of frozen cherry fruits (average during 2007–2019), %

Cultivar	Storage period			LSD_{05}
	after freezing	30 days of storage	90 days of storage	
Vstrecha	7.10 ± 0.11	7.8 ± 0.12	8.1 ± 0.15	0.46
Ozhydanie	6.20 ± 0.07	7.0 ± 0.13	7.4 ± 0.07	0.22
Shalunia	5.70 ± 0.12	5.9 ± 0.11	6.2 ± 0.19	0.54
Siyanets Turovtsevoi	5.90 ± 0.09	6.3 ± 0.11	6.5 ± 0.17	0.46
Griot Melitopolskyi	4.20 ± 0.19	5.1 ± 0.1	5.8 ± 0.15	0.53
Melitopolska Purpurna	4.10 ± 0.09	4.3 ± 0.1	4.3 ± 0.15	0.18
Modnytsia	4.60 ± 0.15	5.1 ± 0.16	5.3 ± 0.16	0.33
Expromt	6.20 ± 0.09	6.9 ± 0.15	7.2 ± 0.18	0.54
Solidarnist	6.80 ± 0.19	7.4 ± 0.25	8.0 ± 0.19	0.70
Igrushka	6.10 ± 0.21	6.9 ± 0.18	7.4 ± 0.19	0.77
Average value	5.7 ± 0.18	6.3 ± 0.16	6.6 ± 0.17	0.75
LSD_{05}	0.36	0.39	0.41	–

It was established that the maximum loss of cell juice occurred immediately after fruit freezing. In cherry fruits this indicator varied from 7.10% (Vstrecha cultivar) to 4.00% (Melitopolska Purpurna cultivar). The obtained results can be explained by physico-chemical and structural characteristics of the investigated cherry cultivars. Fruits with higher values of juice loss contain a larger mass fraction of free moisture compared to those with minimum values of this indicator. During freezing free moisture forms larger ice crystals, which can lead to the destruction of the histological structure. Presumably, the percentage of free moisture in the fruits of Vstrecha cultivar is significantly lower, which contributes to the formation of smaller ice crystals during freezing and ensures better preservation of the histological structure.

In addition, the dry substances of cherries contain significantly more pectin substances, fiber and organic acids compared to sweet cherries. Pectin substances and fiber strengthen intercellular connections, reducing the possibility of cell juice loss after defrosting. The higher content of organic acids creates increased osmotic pressure in the cells, which helps retain moisture inside them and ensures better preservation of the histological structure of the fruits. Therefore, higher losses of juice during cherry fruits defrosting, especially of early cultivars, are caused by a more delicate pulp structure, a lower content of dry substances, in particular pectin, fiber and organic acids, as well as an increased content of free moisture.

During the storage process, changes in the amount of cell juice loss after defrosting were significant, compared to the initial stage. After 30 days of storage, this indicator was 4.3–7.8%, depending on the varietal characteristics of the fruits. The maximum loss of cell juice was found in early ripening cherries. The increase in juice loss in the period from 30–90 days of storage was significant and was within the limits of stationary error. As a result of the analysis of the experimental studies, it was established that among the researched cherry cultivars the minimum loss of cell juice after freezing and three-month storage was observed in Melitopolska Purpurna cultivar, and maximum in Vstrecha cultivar. Therefore, the amount of loss of cell juice during defrosting is an important criterion for assessing the structural integrity of fruits, which affects the quality of frozen semi-finished products.

2.4 Dynamics of dry matter content in cherry fruits during freezing and further storage

The study of the changes in the content of dry substances during freezing and further storage of fruits is important for the production of semi-finished products. According to the available literature, the numerical values of this indicator and its changes affect the qualitative characteristics of the finished product. Taking into account the opinions of scientists regarding the determination of the quality of semi-finished products based on the initial parameters of dry substances, the study of their content in fresh fruit is of great importance. Such research is also important at the stages of storage and for the scientific substantiation of the choice of raw material for the production of semi-finished products. As a research result, it was found that the minimum accumulation of dry substances was observed in dry cherry fruits of Ekspromt cultivar – 16.48% (**Table 2.2**).

The fruits of Griot Melitopolskiy cultivar were characterized by the highest dry matter content of 20.63% ($LSD_{05} = 0.50$). The preservation of dry substances in cherry

fruits immediately after freezing was 70.4–95.8% of their content in fresh fruits. The highest content of dry soluble substances in fresh-frozen fruits was noted in Griot Melitipolskiy cultivar (19.37%). Frozen cherry fruits of Griot Melitopolskiy cultivar both before and after 90 days of storage were characterized by a stable minimum content of dry substances at the level of 19.09–20.63%. The content of this indicator after freezing and at all stages of storage remained stable, and minor changes were statistically unreliable (LSD_{05} = 0.15–1.57%). So, based on the analysis of the experimental data, it can be concluded that the main losses of dry substances, regardless of the varietal characteristics of the fruits, occur at the stage of freezing. Therefore, for the scientific justification of the suitability of the cherry fruit cultivars for freezing and semi-finished products production, it is possible to use the range of data for this stage of control.

Table 2.2 Dynamics of dry substances content in frozen cherry fruits (average for 2007–2019), %

Cultivar	Stages of control				LSD_{05}
	fresh fruits	after freezing	30 days of storage	90 days of storage	
Vstrecha	17.87 ± 2.81	13.21 ± 0.55	13.06 ± 0.40	12.87 ± 0.38	1.58
Ozhydanie	18.31 ± 2.02	16.54 ± 0.20	16.13 ± 0.13	16.02 ± 0.18	0.48
Shalunia	17.94 ± 2.70	16.83 ± 0.30	16.87 ± 0.18	16.68 ± 0.29	0.42
Siyanets Turovtsevoi	19.02 ± 3.53	17.75 ± 0.21	17.45 ± 0.11	17.23 ± 0.07	0.31
Griot Melitopolskyi	20.63 ± 3.31	19.37 ± 0.08	19.14 ± 0.13	19.09 ± 0.11	0.32
Melitopolska Purpurna	17.79 ± 2.81	16.88 ± 0.05	17.08 ± 0.08	17.02 ± 0.07	0.15
Modnytsia	19.05 ± 2.92	17.83 ± 0.09	17.54 ± 0.05	17.24 ± 0.15	0.19
Expromt	16.48 ± 2.53	15.92 ± 0.05	15.02 ± 0.30	15.21 ± 0.11	0.52
Solidarnist	17.03 ± 3.63	15.08 ± 0.11	15.28 ± 0.11	15.37 ± 0.10	0.37
Igrushka	18.58 ± 2.80	15.13 ± 0.08	15.13 ± 0.09	15.04 ± 0.11	0.35
Average value	18.27 ± 3.00	16.45 ± 0.24	16.26 ± 0.24	16.18 ± 0.23	–
LSD_{05}	0.59	0.67	0.52	0.53	–

2.5 Dynamics of sugars content in cherry fruits during freezing and further storage

Sugars and organic acids are the most important dry substances that directly affect the quality of candied fruit. The content of sugars determines the intensity of

dehydration process, the osmotic pressure, as well as the taste properties of the final product. Organic acids, in turn, form a sugar-acid balance and ensure the preservation of fruit texture [19]. From this point of view, the study of changes in the content of these components of the chemical composition during freezing and further storage is of particular importance for the scientific justification of the choice of the raw material for the production of semi-finished products.

In fresh cherry fruits the minimum accumulation of sugars was recorded in the fruits of Ekspromt and Solidarnist cultivars – 10.4 and 10.7% respectively (**Table 2.3**).

Table 2.3 Dynamics of sugars content in frozen cherry fruits (average for 2007–2019), %

Cultivar	Stages of control				LSD_{05}
	fresh fruits	after freezing	30 days of storage	90 days of storage	
Vstrecha	10.80 ± 1.51	8.4 ± 0.53	8.1 ± 0.24	8.0 ± 0.15	1.03
Ozhydanie	11.69 ± 1.90	10.2 ± 0.16	10.1 ± 0.11	10.1 ± 0.17	0.45
Shalunia	10.84 ± 1.92	9.1 ± 0.13	8.9 ± 0.14	8.8 ± 0.14	0.41
Siyanets Turovtsevoi	11.55 ± 2.43	10.3 ± 0.10	10.6 ± 0.09	10.2 ± 0.19	0.39
Griot Melitopolskyi	12.19 ± 2.51	11.0 ± 0.37	10.9 ± 0.48	10.9 ± 0.13	0.99
Melitopolska Purpurna	11.33 ± 2.20	10.4 ± 0.06	10.1 ± 0.09	10.0 ± 0.07	0.26
Modnytsia	11.73 ± 2.84	10.8 ± 0.08	10.5 ± 0.07	10.4 ± 0.09	0.17
Expromt	10.35 ± 1.73	9.3 ± 0.05	9.2 ± 0.06	9.2 ± 0.09	0.29
Solidarnist	10.70 ± 2.72	7.9 ± 0.13	7.8 ± 0.07	7.8 ± 0.10	0.42
Igrushka	11.59 ± 2.21	10.2 ± 0.07	10.0 ± 0.10	10.0 ± 0.09	0.27
Average value	11.28 ± 2.20	9.9 ± 0.15	9.6 ± 0.16	9.5 ± 0.15	–
LSD_{05}	0.50	0.65	0.55	0.39	–

Fruits of Ozhydalie, Solidarnist, Modnytsia, Shalunia, Siyanets Turevtsovoy cultivars were characterized by a high sugar content (11.6–11.8%, LSD_{05} = 0.50). The maximum sugar content in cherry fruits was recorded in Griot Melitopolskiy cultivar – 12.2%. The freezing process is accompanied by statistically significant decrease in sugars content in the fruits regardless of the cultivar and ripening period. The percentage of sugars retention in cherry fruits varied from 90.2 to 92.3% in Griot Melitopolskiy, Modnytsia, Melitopolska Purpurn cultivars. The lowest preservation of sugars (73.8%) was found in the fruits of Solidarnist cultivar. The decrease in sugars content was observed during storage for 30 and 90 days, but these changes were statistically unreliable. So, on the basis of the analysis of the experimental data,

it can be concluded that the main losses of sugars, regardless of the varietal characteristics of the fruits, occur at the stage of freezing. Therefore, for the scientific justification of the suitability of the cherry fruit cultivars for freezing and semi-finished products production, it is possible to use the data range for this stage of control.

2.6 Dynamics of titrated acids content in cherry fruits during freezing and further storage

The share of organic acids in the composition of dry soluble substances of fruits is insignificant. It was established that the main part of the organic acids in fruits is neutralized. It is presented in the form of neutral salts, which do not have the properties of titrated acids. It is the presence of titrated acids (free acids and their acidic and medium salts) that determines the taste of fruits. The average content of titrated acids in fresh cherry fruits is 1.51% (**Table 2.4**).

Table 2.4 Dynamics of titrated acids content in frozen cherry fruits (average for 2007–2019), %

Cultivar	Stages of control				LSD_{05}
	fresh fruits	after freezing	30 days of storage	90 days of storage	
Vstrecha	1.45 ± 0.38	1.27 ± 0.019	1.25 ± 0.01	1.25 ± 0.01	0.07
Ozhydanie	1.51 ± 0.31	1.39 ± 0.013	1.35 ± 0.01	1.33 ± 0.01	0.02
Shalunia	1.49 ± 0.34	1.40 ± 0.032	1.40 ± 0.07	1.39 ± 0.01	0.13
Siyanets Turovtsevoi	1.62 ± 0.30	1.57 ± 0.007	1.55 ± 0.01	1.53 ± 0.01	0.04
Griot Melitopolskyi	1.65 ± 0.31	1.61 ± 0.01	1.62 ± 0.01	1.61 ± 0.01	0.03
Melitopolska Purpurna	1.26 ± 0.31	1.19 ± 0.01	1.17 ± 0.01	1.19 ± 0.01	0.02
Modnytsia	1.26 ± 0.26	1.21 ± 0.01	1.20 ± 0.03	1.20 ± 0.03	0.07
Expromt	1.40 ± 0.22	1.29 ± 0.01	1.27 ± 0.06	1.30 ± 0.01	0.19
Solidarnist	1.79 ± 0.26	1.65 ± 0.01	1.62 ± 0.01	1.70 ± 0.07	0.12
Igrushka	1.65 ± 0.30	1.60 ± 0.07	1.60 ± 0.03	1.60 ± 0.05	0.14
Average value	1.51 ± 0.33	1.42 ± 0.02	1.41 ± 0.02	1.41 ± 0.02	–
LSD_{05}	0.26	0.08	0.10	0.11	–

As a result of the study of fresh cherry fruits quality, it was established that the minimum accumulation of the titrated acids content (1.26%) was observed in

Melitopolska Purpurna and Modnytsia cultivars (LSD_{05} = 0.26%). The maximum content of titrated acids was recorded in Solidarnist cultivar – 1.79%. In general, the content of titrated acids in fresh and frozen fruits showed high stability, regardless of the cultivar and ripening period. The preservation of titrated acids of cherry fruits at the stage immediately after freezing was 87.6–100% of their content in fresh fruits. In cherry cultivar samples after 90 days of storage, the retention of titrated acids relative to freshly frozen fruits was 95.7–100%. A slight increase in the content of titrated acids in the range of 0.03–0.8% was recorded in the Ekspromt and Solidarnist cultivars. The phenomenon of titrated acids stabilization was observed both at the stage of freezing and during a long-term low-temperature storage. Scientists explain this by the fact that the replenishment of acid forms, which were destroyed under the influence of low temperatures in the fruits of cherries and sweet cherries, occurs due to the breakdown of sugars. As a result of the study of cherry fruits suitability for storage according to the content of titrated acids for 90 days, it was established that among the frozen cultivar samples, the highest content was recorded in Griot Melitopolskiy (0.61%) and Solidarnist (0.71%, LSD_{05} = 0.11%). Based on the analysis of the experimental data, it can be concluded that the preservation of titrated acids in fresh and frozen cherry fruits has high stability. Fluctuations in the content of titrated acids in cherry fruits for all cultivars are statistically unreliable. Therefore, as a criterion indicator for scientific justification of the suitability of cherry fruit cultivars for freezing and semi-finished products production, the range data at the stage of control (immediately after freezing) will be used.

2.7 Dynamics of ascorbic acid content in fresh cherry fruits during freezing and further storage

Vitamin C or L-ascorbic acid, is one of the most important phyto-nutrients that determines the biological value of cherry and sweet cherry fruits. Modern technologies of refrigeration processing of plant products are evaluated by the quantitative changes in the content of vitamins in the fruit, in particular, such a labile component as ascorbic acid. The average content of ascorbic acid in fresh cherry samples was 9.17 mg/100 g (**Table 2.5**).

The minimum content of ascorbic acid in fresh cherry fruits was recorded in Griot Melitopolskiy cultivar (8.23 mg/100 g), and the maximum (10.44 mg/100 g) in the fruits of Shalunia cultivar (LSD_{05} = 0.77 mg/100 g). The freezing process was accompanied by a statistically significant decrease in the content of ascorbic acid in the fruits of the studied cultivars. Immediately after freezing, the highest preservation of

ascorbic acid of 43.92% was observed in the cherry fruits samples of Solidarnist cultivar (4.01 mg/100 g), and the lowest preservation of 24.91% was observed in the fruits of Igrushka cultivar (2.18 mg/100 g). The preservation of ascorbic acid after 90 days of storage, compared to losses after freezing, varied in the range of 97.26–99.67%. The highest content of ascorbic acid was recorded in the fruits of Solidarnist cultivar (3.90 mg/100 g). Based on the analysis of the experimental data, it can be concluded that the main losses of ascorbic acid, regardless of the varietal characteristics of the fruit, occur at the stage of freezing. Therefore, as a criterion indicator for the scientific substantiation of the suitability of cherry cultivars for freezing and semi-finished products production the data of this stage of control will be used.

Table 2.5 Dynamics of ascorbic acid content in frozen cherry fruits (average for 2007–2019), %

Cultivar	Stages of control				LSD_{05}
	fresh fruits	after freezing	30 days of storage	90 days of storage	
Vstrecha	9.59 ± 1.34	2.89 ± 0.023	2.82 ± 0.01	2.84 ± 0.01	0.02
Ozhydanie	8.97 ± 1.68	2.34 ± 0.01	2.14 ± 0.01	2.20 ± 0.01	0.03
Shalunia	10.44 ± 2.11	3.56 ± 0.014	3.43 ± 0.01	3.48 ± 0.01	0.04
Siyanets Turovtsevoi	10.10 ± 2.29	3.67 ± 0.02	3.61 ± 0.01	3.61 ± 0.01	0.05
Griot Melitopolskyi	8.23 ± 1.28	2.45 ± 0.01	2.43 ± 0.01	2.44 ± 0.012	0.03
Melitopolska Purpurna	8.44 ± 1.20	3.01 ± 0.01	3.00 ± 0.01	3.00 ± 0.01	0.04
Modnytsia	9.00 ± 1.65	3.02 ± 0.02	2.91 ± 0.21	2.99 ± 0.01	0.34
Expromt	9.00 ± 2.18	2.65 ± 0.01	2.61 ± 0.01	2.59 ± 0.01	0.02
Solidarnist	9.13 ± 1.67	4.01 ± 0.03	3.89 ± 0.04	3.90 ± 0.05	0.04
Igrushka	8.75 ± 1.21	2.18 ± 0.0	2.16 ± 0.01	2.17 ± 0.01	0.03
Average value	9.17 ± 1.77	2.99 ± 0.08	2.90 ± 0.09	2.92 ± 0.08	–
LSD_{05}	0.77	0.06	0.21	0.06	–

2.8 Dynamics of the amount of phenolic compounds in cherry fruits during freezing and further storage

The Ukrainian scientists have discovered 20 phenolic compounds in cherry fruits of various cultivars. In the plant world, phenolic compounds are natural antioxidants that can oxidize vitamin C, which, in turn, stabilizes the action of bioflavonoids. The biochemical synergism of natural antioxidants is one of the factors that ensures

the preservation of the quality of fruit raw materials for a long period. In view of this, it is advisable to assess the quality of cherry cultivars for their suitability for freezing by quantitative changes in phenolic compounds and the degree of their preservation.

The research has established that the content of phenolic compounds in fresh cherry fruits ranged from a minimum of 164.97 mg/100 g in Ekspromt cultivar to a maximum of 243.14 mg/100 g in Melitopolska Purpurna cultivar (**Table 2.6**).

Table 2.6 Dynamics of the sum of phenolic compounds in frozen cherry fruits (average for 2007–2019), mg/100 g

Cultivar	Stages of control				LSD_{05}
	fresh fruits	after freezing	30 days of storage	90 days of storage	
Vstrecha	198.725 ± 28.801	78.36 ± 0.046	72.81 ± 0.011	72.80 ± 0.014	0.076
Ozhydanie	218.823 ± 39.213	85.17 ± 0.019	81.23 ± 0.015	82.67 ± 0.039	0.069
Shalunia	197.487 ± 22.458	89.24 ± 0.018	82.15 ± 0.019	86.14 ± 0.014	0.235
Siyanets Turovtsevoi	224.615 ± 28.776	95.15 ± 0.019	90.36 ± 0.024	94.81 ± 0.018	0.055
Griot Melitopolskyi	193.264 ± 25.662	81.13 ± 0.005	80.99 ± 0.006	81.01 ± 0.14	0.086
Melitopolska Purpurna	243.143 ± 45.721	89.76 ± 0.023	84.12 ± 0.033	83.99 ± 0.048	0.083
Modnytsia	168.275 ± 19.512	83.43 ± 0.013	82.15 ± 0.013	82.29 ± 0.015	0.068
Expromt	164.975 ± 20.670	65.17 ± 0.024	60.35 ± 0.013	60.00 ± 0.148	0.227
Solidarnist	196.584 ± 24.147	70.65 ± 0.012	70.29 ± 0.019	71.01 ± 0.034	0.116
Igrushka	185.474 ± 18.383	80.89 ± 0.036	80.6 ± 0.01	81.02 ± 0.037	0.091
Average value	199.137 ± 36.016	81.90 ± 1.21	78.512 ± 1.15	79.57 ± 1.29	–
LSD_{05}	1.778	0.063	0.048	0.215	–

The highest content of phenolic compounds (224.61 mg/100 g) was recorded in the fruits of Siyanets Turovtsevoi cultivar (LSD_{05} = 0.05 mg/100 g). The freezing process was accompanied by a statistically significant decrease in the content of phenolic substances in cherry fruits, regardless of the ripening period. The preservation of this quality indicator after 90 days of storage ranged from 92.07 to 99.64% compared to the loss of phenolics substances immediately after freezing. At the last stage of storage, the largest amount of phenolic substances was observed in the fruits of Siyanets Turovtsevoi cultivar (94.81 mg/100 g), and the lowest – in Ekspromt cultivar (60.00 mg/100 g, LSD_{05} = 0.21 mg/100 g). After three months of storage during defrosting, an increase in the amount of phenolic compounds in the

range of 0.16–0.50% was recorded in cherry fruits of two cultivars. In the frozen fruits of Igrushka and Solidarnist cultivars, an increase in the content of phenolic compounds by 0.13–0.36 mg/100 g was observed compared to the indicator immediately after freezing (LSD_{05} = 0.09–0.11 mg/100 g). This is due to the breakdown of complex complexes of substances, which include BAS of phenolic nature. Based on the analysis of the experimental data, it can be concluded that the main losses of phenolic substances, regardless of the varietal characteristics of the fruits, occur at the stage of freezing. Therefore, as a criterion indicator for the scientific substantiation of the suitability of cherry fruit cultivars for freezing and semi-finished products production, the data range of this stage of control will be used.

2.9 Sensory evaluation of cherry fruits under freezing and further storage

Sensory evaluation of fresh and frozen cherry fruits ranged from 7.7 to 8.7 points (**Table 2.7**).

Table 2.7 Sensory evaluation of frozen cherry fruits, average for 2007–2019

Cultivar	Stages of control				LSD_{05}
	fresh fruits	after freezing	30 days of storage	90 days of storage	
Vstrecha	8.5 ± 0.05	8.1 ± 0.07	8.1 ± 0.04	8.1 ± 0.03	0.171
Ozhydanie	8.6 ± 0.05	8.0 ± 0.03	8.0 ± 0.03	8.0 ± 0.05	0.135
Shalunia	8.5 ± 0.04	8.2 ± 0.06	8.2 ± 0.07	7.9 ± 0.03	0.129
Siyanets Turovtsevoi	8.5 ± 0.03	7.9 ± 0.1	7.9 ± 0.03	7.8 ± 0.04	0.186
Griot Melitopolskyi	8.7 ± 0.06	8.0 ± 0.03	8.0 ± 0.04	8.0 ± 0.03	0.178
Melitopolska Purpurna	8.6 ± 0.03	7.9 ± 0.1	7.9 ± 0.03	7.9 ± 0.05	0.176
Modnytsia	8.7 ± 0.03	7.8 ± 0.05	7.8 ± 0.04	7.8 ± 0.05	0.101
Expromt	8.5 ± 0.03	7.7 ± 0.05	7.7 ± 0.03	7.7 ± 0.05	0.101
Solidarnist	8.4 ± 0.04	8.0 ± 0.03	8.0 ± 0.03	7.9 ± 0.03	0.097
Igrushka	8.6 ± 0.03	8.1 ± 0.03	8.1 ± 0.04	8.1 ± 0.08	0.146
Average value	8.6 ± 0.04	8.0 ± 0.03	7.9 ± 0.02	7.92 ± 0.02	–
LSD_{05}	0.104	0.182	0.126	0.134	–

Fresh fruits of Griot Melitopolskiy and Modnytsia cultivars received the highest score of 8.7 points (LSD_{05} = 0.10 points). The lowest sensory indicators were recorded for the fruits of Solidarnist cultivar, 8.4 points. The analysis of the sensory characteristics of freshly frozen fruits showed that Shalunia cultivar fruits were the

best immediately after freezing – 8.2 points, the fruits of Igrushka and Meeting cultivars – 8.1 points ($LSD_{05} = 0.18$). Immediately after freezing to the final stage of storage, comparable sensory fruit evaluation was obtained. After three months of storage, the fruits of Vstrecha and Igrushka cultivars retained the highest sensory parameters – 8.1 points. Based on the analysis of the experimental data, it can be concluded that the main losses in the quality of the sensory properties of fruit, depending on the varietal characteristics of fruits, occur at the stage of freezing. Therefore, for the scientific substantiation of the suitability of cherry fruit cultivars for freezing and semi-finished products production, the data range of this stage of control will be the criterion indicator.

2.10 Analysis of the results of determining the suitability of cherry fruit cultivars for freezing and semi-finished products production by the method of multi-criteria optimization

Functional, technological and sensory indicators of the quality of frozen cherry semi-finished products in absolute values are given in **Table 2.8**.

For the scientific substantiation of the choice of cherry fruit cultivars for freezing and semi-finished products production, calculations were carried out according to the developed algorithm. The rank rating of the fruits of cherry cultivars (**Table 2.9**) shows that the values of the target functions were in the range from $\varphi(x_5) = 1.45$ (Griot Melitopolskiy) to $\varphi(x_8) = 4.20$ (Ekspromt).

The highest tenth rank and the least suitability of fruits for candied fruit production from frozen raw materials were determined in Ekspromt cultivar. Frozen fruits of Vstrecha, Solidarnist, Modnytsa, Igrushka, Shalunia, Ozhydanie, Melitopolska Purpurna, Siyanets Turovtsevoi cultivars had 2–8 ranks according to criterion indicators of fruit quality in terms of their suitability for freezing. The values of the target functions in the listed cultivars ranged from $\varphi(x_1) = 3.30$ to $\varphi(x_4) = 1.71$. Therefore, the performed calculations allow to draw a conclusion about the different degrees of cherry cultivars suitability for freezing and semi-finished products production, which is an important stage in choosing the optimal fruit for further production. As a result of qualitative analysis of frozen cherry fruits, it was established that Griot Melitopolskiy cultivar (1st rank) – $j(x_5) = 1.45$ turned out to be the best in terms of the balance of quality indicators. The optimal set of physico-biochemical and organoleptic criteria for cherry fruits included: juice loss immediately after freezing no higher than 4.2%; initial concentration of dry soluble substances – 18.60%; sugars –12.20%; titrated acids – 1.65%; vitamin C – 8.23 mg/100 g; the sum of phenolic compounds – 193.264 mg/100 g; sensory evaluation – 8.7 points.

Table 2.8 Functional and technological indicators of cherry fruits for the calculation of target functions $\varphi(x_1)...\varphi(x_{10})$ when choosing the optimal cultivar of frozen cherry fruits

Alternatives, X_i	Cultivar	Criteria, A_j							Values of target functions, $\varphi(x_i)$	Rank
		The amount of juice loss (%), A_1	Dry soluble substances (%), A_2	Sugars, (V, %), A_3	Titrated acids, (%), A_4	Phenolic substances, (mg/100 g), A_5	Vitamin C, (mg/100 g), A_6	Sensory evaluation, (points), A_7		
		f_1	f_2	f_3	f_4	f_5	f_6	f_7		
X_1	Vstrecha	7.1	15.9	10.8	1.45	198.725	9.59	8.5	3.30	9
X_2	Ozhydanie	6.2	16.3	11.7	1.51	218.82	8.97	8.6	2.41	4
X_3	Shalunia	5.7	15.9	10.8	1.49	197.487	10.44	8.5	2.62	5
X_4	Siyanets Turovtsevoi	5.9	17	11.6	1.62	224.615	10.1	8.5	1.71	2
X_5	Griot Melitopolskyi	4.2	18.6	12.2	1.65	193.264	8.23	8.7	1.45	1
X_6	Melitopolska Purpurna	4.1	15.8	11.3	1.26	243.143	8.44	8.6	2.37	3
X_7	Modnytsia	4.6	17.1	11.7	1.26	168.275	9	8.7	2.75	7
X_8	Expromt	6.2	14.5	10.4	1.4	164.975	9	8.5	4.20	10
X_9	Solidarnist	6.8	15	10.7	1.79	196.584	9.13	8.4	3.18	8
X_{10}	Igrushka	6.1	16.6	11.6	1.65	185.474	8.75	8.6	2.62	6

Table 2.9 Results of determination of the objective functions $\varphi(x_1)...\varphi(x_{10})$ when choosing the optimal cultivar of frozen cherry fruits

Alternatives, X_i	Cultivar	Criteria, A_j							Values of target functions, $\varphi(x_i)$	Rank
		The amount of juice loss (%), A_1	Dry soluble substances (%), A_2	Sugars, (V, %), A_3	Titrated acids, (%), A_4	Phenolic substances, (mg/100 g), A_5	Vitamin C, (mg/100 g), A_6	Sensory evaluation, (points), A_7		
		$\tilde{f}_1$	$\tilde{f}_2$	$\tilde{f}_3$	$\tilde{f}_4$	$\tilde{f}_5$	$\tilde{f}_6$	$\tilde{f}_7$		
X_1	Vstrecha	0.13	0.30	0.32	0.38	0.43	0.58	0.55	3.30	9
X_2	Ozhydanie	0.37	0.39	0.64	0.48	0.69	0.39	0.64	2.41	4
X_3	Shalunia	0.50	0.30	0.32	0.44	0.42	0.84	0.55	2.62	5
X_4	Siyanets Turovtsevoi	0.45	0.54	0.61	0.65	0.76	0.74	0.55	1.71	2
X_5	Griot Melitopolskyi	0.89	0.89	0.82	0.70	0.36	0.16	0.73	1.45	1
X_6	Melitopolska Purpurna	0.92	0.28	0.50	0.08	0.99	0.22	0.64	2.37	3
X_7	Modnytsia	0.79	0.57	0.64	0.08	0.05	0.40	0.73	2.75	7
X_8	Expromt	0.37	0.00	0.18	0.30	0.01	0.40	0.55	4.20	10
X_9	Solidarnist	0.21	0.11	0.29	0.92	0.41	0.44	0.45	3.18	8
X_{10}	Igrushka	0.39	0.46	0.61	0.70	0.27	0.32	0.64	2.62	6
	f_j^-	3.8	14.50	9.90	1.21	164.48	7.73	7.90	–	–
	f_j^+	7.6	19.10	12.70	1.84	243.64	10.94	9.00	–	–
	f_j^{opt}	7.1 (max)	19.1 (max)	12.7 (max)	1.84 (max)	243.64 (max)	10.94 (max)	9.0 (min)	–	–

2.11 Conclusions

The analysis of the quality of cherry fruits in terms of functional, technological and sensory parameters in fresh and frozen state made it possible to determine the optimal storage period of cherry fruits for the production of high-quality semi-finished products.

It was established that the main losses in the quality of raw materials, depending on the varietal characteristics of fruits, occur at the stage of freezing. Therefore, it is advisable to use the data range of this stage as a criterion indicator for the scientific substantiation of cherry cultivars suitability for freezing and semi-finished products production.

The method of multi-criteria optimization made it possible to rank the fruits of different cherry cultivars according to all indicators and to select the cherry fruits of Griot Melitopolskiy cultivar as the most suitable for freezing and semi-finished products production according to a complex of physical, biochemical and organoleptic characteristics.

Based on the results of multi-criteria optimization, a complex of physical, biochemical and organoleptic characteristics was developed, as well as their values, which will serve as markers when assessing the varietal suitability of cherry fruits for freezing and further use and semi-finished products production.

Proposed method of multi-criteria optimization of cherry cultivars based on a complex of functional, technological and sensory indicators, based on the method of geometric convolution of criteria, allows to ensure the objectivity of the assessment and contributes to an effective decision-making when choosing the best cultivar for freezing. This, in turn, helps to optimize the process of choosing the cherry fruits cultivars further use and semi-finished products production.

Further research in the direction of multi-criteria cherry cultivars optimization can be aimed at adapting the method of geometric convolution of criteria to different areas of production. It is also important to expand the criteria for evaluating the quality of cherries, which affect the final indicators of products. Future work may include the development of integrated models that combine sensory analysis data with the results of laboratory studies to create more accurate forecasts of the quality of frozen raw materials. This will make it possible to optimize the processes of choosing cherry fruit cultivars for freezing and semi-finished products production, taking into account modern requirements for the food products quality and safety.

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CHAPTER 3

Chemical composition and properties of vegetable oil blends

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Abstract

Vegetable oils are widely used in food formulations due to their essential role as a source of fat and energy for the human body, as well as their content of vitamins and minerals. The addition of vegetable oils to foods not only improves flavor and texture but also increases the nutritional value of various products. These oils are produced by a variety of methods, typically involving mechanical pressing or extraction processes. The composition of vegetable oils consists primarily of fatty acids, which can be classified as saturated, monounsaturated, and polyunsaturated fats.

The balance of fatty acids plays a critical role in human health, as an optimal ratio of dietary fats is required for various metabolic processes. However, no single vegetable oil provides a perfectly balanced fatty acid profile. Therefore, blending oils in specific proportions can help to achieve a more balanced composition of dietary fats. Such blended oils can be used in a wide range of culinary applications, including cooking, frying, and baking, and offer a versatile and nutritious alternative to traditional oils.

In this study, four vegetable oil blends with a balanced composition of polyunsaturated fatty acids (omega-3:omega-6) were developed: olive oil – rapeseed oil – sunflower oil; linseed oil – olive oil – sunflower oil; corn oil – olive oil – rapeseed oil; and corn oil – linseed oil – olive oil. The acid value, peroxide value, and iodine value of the individual oils and their blends were studied to assess their quality and stability. The acid value of the developed vegetable oil blends ranged from 0.30 to 0.56 mg KOH/g, which were within the acceptable limit of 0.6 mg KOH/g recommended by CODEX STAN 210-1999. Similarly, the peroxide value of the vegetable oil blends varied from 2.3 to 2.9 mmol O_2/kg, which were also well below the acceptable limit of 7 mmol O_2/kg for vegetable oils. The iodine value of the blends ranged from 112 to 145 g I_2/100 g, reflecting the degree of unsaturation of the oils.

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In addition, the chemical composition of the individual vegetable oils and their blends was analyzed, providing further insight into the properties and benefits of using such oil blends in food production. The results confirm that these vegetable oil blends not only offer a favorable fatty acid balance, but also maintain a stable quality, making them suitable for a variety of culinary applications while promoting health-conscious dietary choices.

Keywords

Corn oil, linseed oil, olive oil, rapeseed oil, sunflower oil, fatty acid composition, alpha-linolenic acid, linoleic acid.

3.1 Introduction

Vegetable oils are important nutritional components that provide essential fatty acids, aid in the absorption of fat-soluble vitamins, and serve as a source of energy for consumers. They also contain vitamins E and K, iron, potassium, calcium, phosphorus, and other minerals, as well as fatty acids [1]. In addition, as an ingredient, vegetable oil can influence the texture, stability, and sensory properties of foods [2]. Consumers prefer cold-pressed oils as this process results in less alteration of the bioactive components in the oil compared to refined oils [3]. Despite the wide range of vegetable oils available on the market, none of them meet the recommended fatty acid ratio.

Fats are the primary source of energy for humans. They influence the quality of food, play a crucial role in the formation of taste and aroma sensations, and also contribute to the feeling of satiety. According to recommendations [4], fat intake should provide 20–35% of the total energy required for the normal functioning of an adult human body. The biological value of fat is determined by its fatty acid composition and the ratio of saturated (SFA), monounsaturated (MUFA), and polyunsaturated (PUFA) fatty acids. The World Health Organisation (WHO) recommends a balanced proportion of dietary fats (SFA:MUFA:PUFA) of 1:1.5:1, as well as a ratio of omega-3 fatty acid (alpha-linolenic acid) to omega-6 fatty acid (linoleic acid) of 1:5–10 [4, 5]. Omega-3 and omega-6 fatty acids are essential because the human body cannot produce them, and they must be obtained from the diet [6].

Most vegetable oils (rapeseed, soybean, corn, sunflower) are sources of omega-6 fatty acid in the form of linoleic acid and have a low content of omega-3 fatty acid [7]. Lipids in edible oils are sensitive to autoxidation and photo-oxidation during processing and storage, leading to the development of undesirable flavours, the formation of toxic compounds, and a reduction in the nutritional value of the food

product [8]. Vegetable oils have a high biodegradability (95%) [9], a high flash point of 275–320°C [10], and a smoke point of 175–255°C [11].

Vegetable oils do not have an ideal fatty acid profile (**Table 3.1**), which is why blending is an effective way to balance their fatty acid composition. This approach makes it possible to create complex systems from high-quality vegetable oils, enriching them with fat-soluble vitamins, phospholipids, and spices, and enabling them to be used in the manufacture of fatty foods. Blended oils can be consumed directly as food and used as a fat base for the development of functional foods. Blended oils, produced in Ukraine and other countries, are classified into vitaminized blended oils with a balanced PUFA composition, stabilized with synthetic components to prevent oxidative spoilage, and vitaminized blended oils enriched with biologically active substances (rosehip oil, pumpkin oil, pine nut oil, and linseed oil), which do not have a balanced PUFA composition.

Table 3.1 Fatty acid composition of vegetable oils

Vegetable oils	Mean, %			References
	SFA	MUFA	PUFA	
Almond oil	5.77	67.75	26.58	R. Yang et al. [12]
Coconut oil	92.92	5.84	1.28	K. Chowdhury et al. [13]
Corn oil	15.39	31.34	52.82	R. Yang et al. [12]
Grape seed oil	11.07	17.07	71.80	R. Yang et al. [12]
Linseed oil	12.71	23.54	63.20	R. Yang et al. [12]
Mustard oil	15.94	49.57	36.62	K. Chowdhury et al. [13]
Olive oil	16.16*	67.33*	14.84*	B. Marongui et al. [14]
Palm oil	46.34	41.46	11.84	K. Chowdhury et al. [13]
Pumpkin seed oil	18.84	28.25	52.92	R. Yang et al. [12]
Rapeseed oil	7.00	61.00	32.00	L. Sakhno [15]
Soybean oil	18.26	23.28	57.86	K. Chowdhury et al. [13]
Sunflower oil	8.80	31.50	59.50	V. Kostik et al. [16]
Walnut oil	8.38	18.24	68.89	R. Yang et al. [12]

*Note: *calculated by the authors*

The typical Western-type diet is characterized by 5 to 15 times higher intake of linoleic acid (LA) than alpha-linolenic acid (ALA) [17]. This is because consumers' diets often contain high levels of sunflower, olive, and corn oils, which are rich in LA,

and virtually no foods rich in ALA, such as linseed and rapeseed oils (**Table 3.2**). At the same time, ALA is the main source of omega-3 PUFAs in the diet of people who do not regularly consume oily fish [18].

Table 3.2 The content of ALA and LA in vegetable oils

Vegetable oils	Mean, %		ALA: LA ratio	References
	ALA	LA		
Corn oil	1.0	57.0	1:57	L. Sakhno [15]
Linseed oil	51.5*	15.9*	1:0.3	M. Nykter et al. [19]
Olive oil	1.0	9.0	1:9	L. Sakhno [15]
Rapeseed oil	11.0	21.0	1:1.9	L. Sakhno [15]
Sunflower oil	1.0	71.0	1:71	L. Sakhno [15]

*Note: *calculated by the authors for commercial linseed oil*

It is important to develop blended vegetable oils with a balanced fatty acid composition in line with WHO recommendations. These blends can be consumed by adding them to various foods, especially in the form of salad dressings.

3.2 Physicochemical and sensory properties of vegetable oils

Each type of vegetable oil has its own unique chemical composition, physical and nutritional properties, offering specific benefits and health effects [20]. Therefore, consumers can choose different types of vegetable oil to suit their individual needs.

3.2.1 Corn oil

Corn oil belongs to the group of vegetable oils with a high content of linoleic acid (more than 52.0%) and oleic acid (30.5%), but it contains only 1.0% of linolenic acid [21]. Corn oil contains approximately 60% PUFAs, 25% MUFAs, and 15% SFAs, as well as a total of 1.3–2.3% phytosterols, tocopherols, tocotrienols, and squalene [21]. The squalene content of corn oil ranges from 6.8 to 256.8 mg per 100 g, and the β-carotene content is approximately 0.1 mg/kg [20]. The total phenolic content of corn oil is 12.6–53.6 mg/kg [20]. The physical properties of corn oil

are as follows: density 914 g/L, viscosity 35.4 cSt, flash point 259°C and higher heating value 39.66 MJ/kg [22]. Corn oil has a pleasant smell and taste. Its color ranges from pale yellow to reddish brown. Corn oil is important for human health due to its unique characteristics and nutritional properties [23].

3.2.2 Linseed oil

Linseed oil is one of the richest sources of omega-3 PUFAs [24]. In the health food market, linseed oil is becoming increasingly popular as a functional food due to its health benefits. Due to its beneficial properties, linseed oil is used not only in functional food products but also in the production of nutraceutical, pharmaceutical, and cosmetic products [24]. Linseed oil has a fatty acid profile with a low content of saturated fats (9%), a moderate content of MUFAs (about 18%), and a high content of PUFAs (about 73%), with approximately 16% of fatty acids being omega-6 (mainly LA) and 57% being omega-3 (ALA) [25]. The high ALA content leads to oxidative instability of linseed oil [26]. Due to its instability, linseed oil is not recommended for sole use in food production [27]. The squalene content of linseed oil is 2.4–83.0 mg/100 g [20]. The carotenoid content of linseed oil is as follows (mg/kg): β-carotene 34.9–76.9, lutein 11.6, and zeaxanthin 1.1 [20]. The total phenolic content of linseed oil is 4.0–3073.0 mg/kg [20]. The physical properties of linseed oil are as follows: density 921 g/L, viscosity 27.2 cSt, flash point 247°C and higher heating value 39.5 MJ/kg [22]. Linseed oil is a colorless to yellowish oil with a light hay-like smell, a faint fishy aroma, and a bitter taste.

3.2.3 Olive oil

Olive oil is known for its health benefits due to its significant content of functionally active compounds, including phenolic compounds (tyrosol, oleocanthal, oleuropein, hydroxytyrosol, and oleuropein aglycone) and biologically active carotenoids [28]. The carotenoid content of olive oil is as follows (mg/kg): β-carotene 36.0, lutein 0.8–4.4, zeaxanthin 0.8, lycopene 0.8, and α-carotene 3.6 [20]. The squalene content of olive oil ranges from 153.4 to 747.4 mg per 100 g [20]. The total phenolic content of olive oil is 23.0–2180.0 mg/kg [20]. The physical properties of olive oil are as follows: density 918 g/L, viscosity 29.8 cSt, flash point 231°C and higher heating value 39.5 MJ/kg [22]. Olive oil is mainly composed of triacylglycerols (98%) and a number of substances including free fatty acids, phenols, tocopherols, sterols,

phospholipids and volatile compounds [29]. Oleic acid accounts for 60–80% of the total fatty acid composition of olive oil [30]. Olive oil has a golden color with various shades of green.

3.2.4 Rapeseed oil

Rapeseed oil is the third most popular edible oil in the world due to its high nutritional value, mainly due to its high content of unsaturated fatty acids, especially PUFAs [31]. In addition to unsaturated fatty acids, rapeseed oil contains functional components such as vitamin E, flavonoids, squalene, carotenoids, glucoraphanin, sterols, phospholipids, and ferulic acid, all of which have health benefits [31]. The squalene content of rapeseed oil is 2.1–12.5 mg/100 g [20]. The carotenoid content of rapeseed oil is as follows (mg/kg): β-carotene 6.0–18.8, lutein 32.6–95.0, and zeaxanthin 1.2 [20]. The total phenolic content of rapeseed oil is 10.3–1654.5 mg/kg [20]. The physical properties of rapeseed oil are as follows: density 912 g/L, viscosity 37.3 cSt, flash point 258°C and higher heating value 39.52 MJ/kg [22]. More than one hundred aroma-active compounds have been identified in rapeseed oil, including aldehydes, ketones, acids, esters, alcohols, phenols, pyrazines, furans, indole, pyridines, pyrrolines, thiazoles, thiophene, alkenes and others, which contribute to its flavor [32]. The color of rapeseed oil varies from yellow to brown, depending on the production method. Rapeseed oil has a very mild flavor, but heating this oil can lead to the formation of off-flavors, often characterized by a fishy smell.

3.2.5 Sunflower oil

Sunflower oil is the main type of vegetable oil produced in Ukraine. It is widely used as a food product in its natural form in cooking. Sunflower oil has high nutritional value due to its high LA content [32], as well as its elevated levels of vitamin E and phytosterols compared to other oils [28]. The tocopherol content of sunflower oil ranges from 270 to 1240 mg/kg, which increases its nutritional value [33]. Sunflower oil contains 5.3–27.1 mg/100 g of squalene and 11.6–12.4 mg/kg of lutein [20]. The total phenolic content of sunflower oil ranges from 4.8 to 1920.0 mg per kg [20]. The physical properties of sunflower oil are as follows: density 916 g/l, viscosity 33.9 cSt, flash point 262°C and higher heating value 39.59 MJ/kg [22]. Unrefined sunflower oil has a light yellow color, while refined oil has a pale yellow hue. It has a pleasant flavor and aroma which can be easily removed by deodorization.

3.3 Materials and methods

3.3.1 Materials

Samples of refined olive oil (OO), rapeseed oil (RO), and sunflower oil (SO), as well as unrefined corn oil (CO), and linseed oil (LO), were analyzed. The vegetable oils were purchased from a local supermarket (Lutsk, Ukraine).

The blended oil samples were prepared by mixing three types of vegetable oils in the required proportions. The ratio of vegetable oils in the blend was calculated using the following Equations, taking into account the recommended ratios of omega-3:omega-6 (1:10) and MUFA:PUFA (1.5:1) in foods [4, 5]:

$$x_1 + x_2 + x_3 = 100, \tag{3.1}$$

$$\frac{a_1x_1 + a_2x_2 + a_3x_3}{b_1x_1 + b_2x_2 + b_3x_3} = \frac{1}{10}, \tag{3.2}$$

$$\frac{c_1x_1 + c_2x_2 + c_3x_3}{d_1x_1 + d_2x_2 + d_3x_3} = \frac{1.5}{1}, \tag{3.3}$$

where x_1, x_2, and x_3 are the contents of the three vegetable oils in the blended oil (%); a_1, a_2, and a_3 are the contents of ALA (omega-3) in x_1, x_2, and x_3 vegetable oils, respectively (%); b_1, b_2, and b_3 are the contents of LA (omega-6) in x_1, x_2, and x_3 vegetable oils, respectively (%); c_1, c_2, and c_3 are the contents of MUFAs in x_1, x_2, and x_3 vegetable oils, respectively (%); d_1, d_2, and d_3 are the contents of PUFAs in x_1, x_2, and x_3 vegetable oils, respectively (%).

The results of the calculation of the content of vegetable oils in the blend are shown in **Table 3.3**.

Table 3.3 Content of vegetable oils in the blend

Oil blend samples	Vegetable oil content, %				
	CO	LO	OO	RO	SO
OBS1	–	–	45.15	22.00	32.85
OBS2	–	4.01	60.62	–	35.37
OBS3	40.77	–	38.13	21.10	–
OBS4	43.78	3.83	52.39	–	–

Taking into account the required fatty acid composition in the oil blends, four samples of oil blends were defined, namely: oil blend OBS1 (OO–RO–SO); oil blend

OBS2 (LO–OO–SO); oil blend OBS3 (CO–OO–RO); oil blend OBS4 (CO–LO–OO). The recommended ratios of omega-3:omega-6 (1:10) and SFA:PUFA (1.5:1) were maintained in all oil blend samples (**Table 3.4**).

Table 3.4 Content and ratio of MUFAs and PUFAs in samples of vegetable oil blends

Oil blend samples	Content of PUFAs, %		ALA:LA ratio	Content, %		MUFA:PUFA ratio
	ALA	LA		MUFA	PUFA	
OBS1	3.20	32.00	1.0:10.0	52.81	35.21	1.5:1.0
OBS2	3.11	31.10	1.0:10.0	51.44	34.29	1.5:1.0
OBS3	3.11	31.10	1.0:10.0	51.32	34.21	1.5:1.0
OBS4	3.02	30.24	1.0:10.0	49.90	33.27	1.5:1.0

*Note: to calculate the oil ratio in the blend, the PUFA content of the vegetable oils was considered equal to the sum of the ALA and LA content (**Table 3.2**), while the MUFA content of the vegetable oils was taken from the data in **Table 3.1***

3.3.2 Methods

3.3.2.1 Acid value

The acid value of vegetable oils is the number of milligrams of potassium hydroxide (KOH) necessary to neutralize the free acids presented in 1 g of test sample. The acid value of vegetable oils and their blends was determined by the method according to ISO 660:2020 "Animal and vegetable fats and oils –Determination of acid value and acidity". The oil or blend sample was dissolved in a suitable solvent mixture, and the acids present are titrated with an ethanolic solution of potassium hydroxide.

3.3.2.2 Peroxide value

The peroxide value of vegetable oils and their blends was determined by the method according to ISO 3960:2017 "Animal and vegetable fats and oils – Determination of peroxide value – Iodometric (visual) endpoint determination". The oil or blend sample was dissolved in isooctane and glacial acetic acid, and potassium iodide was added. The iodine liberated by the peroxides was determined visually with a starch indicator and a sodium thiosulfate standard solution. The endpoint of the titration was determined visually. The peroxide value was expressed in millimoles (mmol) of active oxygen per kilogram of oil (mmol O_2/kg).

3.3.2.3 Iodine value

The iodine value of vegetable oils and their blends was determined by the method according to ISO 3961:2018 "Animal and vegetable fats and oils – Determination of iodine value". The oil or blend sample was dissolved in a solvent, and Wijs reagent was added. After a specified time, potassium iodide and water were added, and the liberated iodine was titrated with sodium thiosulfate solution. The iodine value was calculated in grams per 100 g of vegetable oil or blend using equation

$$w_I = \frac{12.69c(V_1 - V_2)}{m}, \tag{3.4}$$

where c is the concentration of the sodium thiosulfate solution (mol/l); V_1 is the volume of sodium thiosulfate solution used for the blank test (ml); V_2 is the volume of sodium thiosulfate solution used for the determination (ml); m is the mass of the vegetable oil or blend sample (g).

3.3.2.4 Fatty acid content

The fatty acid content of vegetable oils and their blends was determined by gas chromatography – mass spectrometry (GC–MS) using a Shimadzu GCMS2030-QP2020NX gas chromatograph. Helium was used as carrier gas at a flow rate of 1.18 mL/min. The temperature of the injector was 250°C. The temperature program was held at 80°C for 1 min, increased to 250°C at 15°C/min and held for 8 min, and increased to 310°C at 20°C/min and held for 10 min. The mass spectrometric conditions were ion source and interface temperatures of 250°C and 300°C, respectively; the measurements were conducted in the full scan mode (40–900 m/z).

The method was performed according to ISO 12966-1 "Animal and vegetable fats and oils – Gas chromatography of fatty acid methyl esters – Part 1: Guidelines on modern gas chromatography of fatty acid methyl esters". The Shimadzu GC–MS Solution Analysis software was used to process the collected raw data, including peak area integration and normalization, to obtain a data matrix containing sample information and relative intensities of the compounds [34]. The NIST/EPA/NIH mass spectrometer library was used to identify the resolved components.

3.3.2.5 Statistical analysis and calculations

All data reported as mean ± standard deviation (SD). Statistical analysis and calculations were conducted using the Mathcad 14 software.

3.4 Results and discussion

The highest acid values were found in unrefined linseed oil (0.86 ± 0.04 mg KOH/g) and unrefined corn oil (0.84 ± 0.05 mg KOH/g) (**Table 3.5**). Refined oils had acid values ranging from 0.28 to 0.56 mg KOH/g, which is 33–67% lower than in unrefined oils. Among refined oils, the highest acid value was found in rapeseed oil (0.56 ± 0.02 mg KOH/g). Olive and sunflower oils had the same acid value of 0.28 mg KOH/g.

According to N. A. Fakhri and H. K. Qadir [35], the acid values of vegetable oils were as follows: CO – 0.51 mg KOH/g; OO – 3.45–18.93 mg KOH/g; RO – 0.65 mg KOH/g; SO – 0.52–0.80 mg KOH/g. The acid value of linseed oil, according to [36], ranged from 2.10 to 3.04 mg KOH/g. Therefore, the acid value of vegetable oils can vary widely depending on the raw material properties and the oil production method.

The acid value is a crucial parameter for assessing the quality of the vegetable oil [37]. A lower acid value indicates better oil quality and freshness, as well as its stability over time, providing protection against rancidity and peroxidation [38]. Vegetable oils with an acid value above 3 mg KOH/g are considered unfit for human consumption in some countries [37]. According to the Standard for Named Vegetable Oils (CODEX STAN 210-1999), the maximum acceptable oil acid value is 0.6 mg KOH/g for refined oils and 4.0 mg KOH/g for cold-pressed and virgin oils.

Table 3.5 Acid value, peroxide value and iodine value of vegetable oils

Parameter	Vegetable oil				
	CO	LO	OO	RO	SO
Acid value, mg KOH/g	0.84 ± 0.05	0.86 ± 0.04	0.28 ± 0.03	0.56 ± 0.02	0.28 ± 0.01
Peroxide value, mmol O_2/kg	3.4 ± 0.1	4.6 ± 0.1	2.0 ± 0.1	3.8 ± 0.0	2.5 ± 0.1
Iodine value, g I_2/100 g	115 ± 4	172 ± 5	90 ± 4	108 ± 3	128 ± 4

The highest peroxide value was found in linseed oil (4.6 ± 0.1 mmol O_2/kg), while the lowest peroxide value was observed in olive oil (2.0 ± 0.1 mmol O_2/kg) (**Table 3.5**). Sunflower oil had a peroxide value of 2.5 ± 0.1 mmol O_2/kg, while corn oil and rapeseed

oil had peroxide values of 3.4±0.1 and 3.8±0.0 mmol O_2/kg, respectively. The peroxide value is commonly used as an index to monitor the oxidation of vegetable oils and to assess oil quality during processing, storage and marketing [39]. High peroxide values indicate increased levels of oxidative rancidity in vegetable oils and suggest a lack of or low levels of antioxidants [38]. According to R. Vidrih, S. Vidakovič, and H. Abramovič [40], a peroxide value of 10 mmol O_2/kg was considered the upper limit for unrefined oils, while a peroxide value of 7 mmol O_2/kg was the upper limit for refined oils.

The iodine value of unrefined vegetable oils ranged from 115 to 172 g I_2/100 g, while refined oils had values between 90 and 128 g I_2/100 g (**Table 3.5**). The highest iodine value was found in linseed oil at 172±5 g I_2/100 g, while olive oil had the lowest iodine value at 90±4 g I_2/100 g. According to previous studies [41], the iodine values of vegetable oils were as follows: CO 110.81 g I_2/100 g; OO 72.00–101.25 g I_2/100 g; RO 162.86 g I_2/100 g; SO 118.65–159.55 g I_2/100 g. The iodine value of linseed oil was found to be between 173.39 and 178.83 g I_2/100 g by N. Beema et al. [36]. The higher the level of unsaturation, the higher the iodine value and the greater the tendency of the vegetable oil to become rancid through oxidation [38].

The acid value of the developed oil blends ranged from 0.30 to 0.56 mg KOH/g (**Table 3.6**). The acid value of the blend depended on the vegetable oils contained in it. The higher the content of oils with a higher acid value in the blend, the higher the acid value of the blend itself. The highest acid value (0.56±0.02 mg KOH/g) was found in the OBS3 blend, which contained corn oil (40.77%), olive oil (38.13%) and rapeseed oil (21.10%) with acid values of 0.84, 0.28, and 0.56 mg KOH/g, respectively. The lowest acid value (0.30±0.03 mg KOH/g) was found in the OBS2 blend containing olive oil (60.62%), sunflower oil (35.37%) and linseed oil (4.01%) with acid values of 0.28, 0.28 and 0.86 mg KOH/g, respectively. Therefore, the maximum level of 0.6 mg KOH/g recommended by CODEX STAN 210-1999 was not exceeded in any of the oil blends.

Table 3.6 Acid value, peroxide value and iodine value of vegetable oil blend

Parameter	Vegetable oil blend			
	OBS1	OBS2	OBS3	OBS4
Acid value, mg KOH/g	0.31±0.01	0.30±0.03	0.56±0.02	0.53±0.01
Peroxide value, mmol O_2/kg	2.4±0.1	2.3±0.0	2.9±0.0	2.8±0.1
Iodine value, g I_2/100 g	112±5	140±4	114±5	145±6

The peroxide value of the oil blends ranged from 2.3 to 2.9 mmol O_2/kg (**Table 3.6**). The OBS3 and OBS4 blends had the highest peroxide values of 2.9±0.0 and

2.8 ± 0.1 mmol O_2/kg, respectively. The peroxide value of the OBS3 blend was attributed to its high content of corn oil (40.77%) and rapeseed oil (21.10%), which had high peroxide values of 3.4 and 3.8 mmol O_2/kg, respectively. The OBS4 blend also contained a high proportion of corn oil (43.78%) with a high peroxide value, as well as linseed oil (3.83%) with a peroxide value of 4.6 mmol O_2/kg. The peroxide value of the developed oil blends did not exceed the highest acceptable value recommended by previous studies [40], which was 7 mmol O_2/kg.

The iodine value of the vegetable oil blends also depended on the composition of the blend and ranged from 112 to 145 g I_2/100 g (**Table 3.6**). The highest iodine values were found in the blends OBS2 (140 ± 4 g I_2/100 g) and OBS4 (145 ± 6 g I_2/100 g). These two blends contained linseed oil, which had the highest iodine value (172 ± 5 g I_2/100 g). The OBS1 and OBS3 blends had iodine values of 112 ± 5 and 114 ± 5 g I_2/100 g, respectively. Olive oil and rapeseed oil had the highest total content in these blends (for OBS1: total OO+RO – 67.15%; for OBS3: total OO+RO – 59.23%). These oils had the lowest iodine values of 90 ± 4 (OO) and 108 ± 3 (RO) g I2/100 g.

Table 3.7 shows the results of the determination of the fatty acid content of vegetable oils available on the Ukrainian market. The highest content of saturated fatty acids was found in olive oil (17.35%), and the lowest in rapeseed oil (8.73%). B. Marongui et al. [14] found that the average content of saturated fatty acids in olive oil was 16.16%. According to L. Sakhno [15], rapeseed oil contained 7.0% of saturated fatty acids. In vegetable oils, palmitic acid (5.62–9.25%) and stearic acid (1.98–7.52%) had the highest content among the saturated fatty acids. The content of arachidic acid and behenic acid in the oils was 0.31–0.82% and 0.31–0.98% respectively. Lignoceric acid (0.30%) was only found in corn oil.

The monounsaturated fatty acid content of the analyzed oils ranged from 17.54% to 62.98% (**Table 3.7**). The highest content of monounsaturated fatty acids was found in rapeseed oil (62.98%) and olive oil (62.40%), while the lowest was in linseed oil (17.54%). According to previous studies, the content of monounsaturated fatty acids in vegetable oils was as follows: linseed oil 23.54% [12], rapeseed oil 61.00% [15], and olive oil 67.33% [14]. Palmitoleic acid was only found in rapeseed oil (0.12%) and sunflower oil (0.08%). The content of oleic acid was ranged from 17.26% (linseed oil) to 62.40% (olive oil). Erucic acid and nervonic acid were only found in corn oil, at 1.80% and 0.46%, respectively. The content of eicosenoic acid in vegetable oils ranged from 0.22% to 3.89%. No eicosenoic acid was found in olive oil.

The highest content of polyunsaturated fatty acids was found in linseed oil (66.83%) and sunflower oil (55.56%) (**Table 3.7**). Olive oil and rapeseed oil contained the least polyunsaturated fatty acids, with 20.25% and 28.29%, respectively. Linseed oil was a source of alpha-linolenic acid (52.72%), while sunflower oil and corn

oil were sources of linoleic acid, with contents of 55.56% and 47.84%, respectively. No alpha-linolenic acid was found in sunflower oil.

Table 3.7 Fatty acid content (%) of vegetable oils

Fatty acid	Vegetable oil				
	CO	LO	OO	RO	SO
SFA					
Palmitic acid ($C_{16:0}$)	7.89	7.37	9.25	5.62	5.87
Stearic acid ($C_{18:0}$)	4.03	7.52	6.74	1.98	4.55
Arachidic acid ($C_{20:0}$)	0.56	0.31	0.38	0.82	0.35
Behenic acid ($C_{22:0}$)	0.82	0.43	0.98	0.31	0.91
Lignoceric acid ($C_{24:0}$)	0.30	ND	ND	ND	ND
Total	**13.60**	**15.63**	**17.35**	**8.73**	**11.68**
MUFA					
Palmitoleic acid ($C_{16:1}$)	ND	ND	ND	0.12	0.08
Oleic acid ($C_{18:1}$)	31.60	17.26	62.40	60.94	32.46
Eicosenoic acid ($C_{20:1}$)	3.89	0.28	ND	1.92	0.22
Erucic acid ($C_{22:1}$)	1.80	ND	ND	ND	ND
Nervonic acid ($C_{24:1}$)	0.46	ND	ND	ND	ND
Total	**37.75**	**17.54**	**62.40**	**62.98**	**32.76**
PUFA					
ALA	0.81	52.72	1.53	9.08	ND
LA	47.84	14.11	18.72	19.21	55.56
Total	**48.65**	**66.83**	**20.25**	**28.29**	**55.56**
ALA:LA ratio	1:59.1	1:0.3	1:12.2	1:2.1	–
MUFA:PUFA ratio	0.8:1	0.3:1	3.1:1	2.2:1	0.6:1

Note: ND – not detected

The ALA:LA ratio in the vegetable oils was as follows: corn oil 1:59.1, linseed oil 1:0.3, olive oil 1:12.2, rapeseed oil 1:2 (**Table 3.7**). Only in olive oil is the ALA:LA ratio close to the recommended 1:5–10 [4, 5]. The ALA:LA ratio found for the vegetable oils studied, particularly olive oil and rapeseed oil, differs somewhat from the ratios reported by other researchers for oils (**Table 3.2**).

The MUFA:PUFA ratio in the vegetable oils was as follows: corn oil 0.8:1, linseed oil 0.3:1, olive oil 3.1:1, rapeseed oil 2.2:1, sunflower oil 0.6:1 (**Table 3.7**). Therefore, this ratio does not correspond to the recommended value of 1.5:1 in any of the vegetable oils studied [4, 5]. The MUFA:PUFA ratios found by researchers in other studies

were as follows: corn oil 0.6:1 [12], linseed oil 0.4:1 [12], olive oil 4.5:1 [14], rapeseed oil 1.9:1 [15], sunflower oil 0.5:1 [16] (**Table 3.1**). Therefore, the greatest discrepancy in MUFA:PUFA ratio values between the oils studied and those studied by other researchers is observed for olive oil.

The fatty acid composition of the developed vegetable oil blends is shown in **Table 3.8**. The content of saturated fatty acids in the oil blends ranged from 13.82% to 15.96%. The highest content of saturated fatty acids was found in the samples OBS4 and OBS2, with 15.96% and 15.77%, respectively. This is explained by the high content of olive oil in these blends, 52.39% (OBS4) and 60.62% (OBS2), which had the highest content of saturated fatty acids at 17.35%. The oil blend OBS1 had the lowest content of saturated fatty acids at 13.82%, due to the presence in its composition of sunflower oil (32.85%) and rapeseed oil (22.00%), both of which had a relatively low content of saturated fatty acids, 11.68% and 8.73%, respectively. The oil blends contained the highest levels of palmitic acid (7.51–8.43%) and stearic acid (5.03–6.27%), while the levels of arachidic acid and behenic acid did not exceed 1%.

Table 3.8 Fatty acid content (%) of vegetable oil blend

Fatty acid	Vegetable oil blend			
	OBS1	OBS2	OBS3	OBS4
SFA				
Palmitic acid ($C_{16:0}$)	7.51	8.18	8.03	8.43
Stearic acid ($C_{18:0}$)	5.03	6.27	5.03	6.08
Arachidic acid ($C_{20:0}$)	0.47	0.36	0.59	0.46
Behenic acid ($C_{22:0}$)	0.81	0.96	0.83	0.99
Total	**13.82**	**15.77**	**14.48**	**15.96**
MUFA				
Palmitoleic acid ($C_{16:1}$)	ND	ND	ND	ND
Oleic acid ($C_{18:1}$)	51.98	49.51	49.24	47.01
Eicosenoic acid ($C_{20:1}$)	0.58	0.11	2.00	1.75
Erucic acid ($C_{22:1}$)	ND	ND	0.75	0.81
Total	**52.56**	**49.62**	**51.99**	**49.57**
PUFA				
ALA	2.69	3.04	2.83	3.18
LA	30.93	31.57	30.70	31.29
Total	**33.62**	**34.61**	**33.53**	**34.47**
ALA:LA ratio	1:11.5	1:10.4	1:10.8	1:9.8
MUFA:PUFA ratio	1.6:1	1.4:1	1.6:1	1.4:1

Note: ND – not detected

The highest content of monounsaturated fatty acids was found in samples OBS1 (52.56%) and OBS3 (51.99%) (**Table 3.8**). These samples contained olive oil and rapeseed oil, which had the highest content of monounsaturated fatty acids, 62.40% and 62.98%, respectively. Sample OBS2 had the lowest content of monounsaturated fatty acids (49.62%) because it contained linseed oil and sunflower oil, which had relatively low contents of monounsaturated fatty acids, 17.54% and 32.76%, respectively. All samples had a high content of oleic acid (47.01–51.98%), while the content of eicosenoic acid ranged from 0.11% to 2.00%. Erucic acid was only detected in samples OBS3 (0.75%) and OBS4 (0.81%), while palmitoleic acid was not detected in any of the samples.

The polyunsaturated fatty acid content of the oil blends ranged from 33.53% (OBS3) to 34.61% (OBS2) (**Table 3.8**). Sample OBS4 had the highest alpha-linolenic acid content (3.18%), while sample OBS1 had the lowest (2.69%). The oil blend OBS2 contained the highest content of linoleic acid (31.57%). At the same time, the alpha-linolenic acid content of the developed oil blends differed by less than 0.5% and the linoleic acid content by less than 1.0%. The ALA:LA ratio in the samples ranged from 1:9.8 to 1:11.5, with the recommended value being 1:10 (used to calculate the oil ratio in the blend). The MUFA:PUFA ratio in the samples ranged from 1.4:1 to 1.6:1 with the recommended value being 1.5:1 (used to calculate the oil ratio in the blend). Therefore, the oil blends developed provide the recommended ALA:LA and MUFA:PUFA ratios.

3.5 Conclusions

The importance of oil blending lies in the ability to balance the fatty acid composition of vegetable oils. Research has led to the development of oil blends with a well-balanced ratio of monounsaturated and polyunsaturated fatty acids, as well as a harmonious balance of omega-3 and omega-6 fatty acids. Each oil blend contains three vegetable oils such as refined olive oil, rapeseed and sunflower oil, as well as unrefined corn oil and linseed oil, carefully selected based on their fatty acid profiles. The acid value (0.30–0.56 mg KOH/g), peroxide value (2.3–2.9 mmol O_2/kg), and iodine value (112–145 g I_2/100 g) of the developed oil blends were tested, with all values falling within the recommended ranges.

In the oil blends, saturated fatty acids ranged from 13.82% to 15.96%, with palmitic acid and stearic acid being the most abundant. The monounsaturated fatty acid content of the developed oil blends ranged from 49.57% to 52.5%, while the oleic acid content varied from 47.01% to 51.98%. The alpha-linolenic acid content ranged from 2.69% to 3.18%, while the linoleic acid content was 30.70–31.57%.

The developed blends of vegetable oils are recommended for use in culinary practice due to their optimal nutritional profiles. Specifically, the blends of flaxseed oil (4.01%) – olive oil (60.62%) – sunflower oil (35.37%), and corn oil (43.78%) – flaxseed oil (3.83%) – olive oil (52.39%) demonstrate the most favorable ratios of alpha-linolenic acid to linoleic acid, as well as monounsaturated to polyunsaturated fatty acids. These proportions align well with current dietary recommendations, making the blends ideal for promoting balanced nutrition in everyday cooking.

Further research should focus on the development of oil blends for a wider range of culinary applications. For example, flavored oil blends could be tested where herbs and spices are incorporated to enhance the aromatic properties. In addition, the vegetable oil blends developed can be further tailored for specific applications such as salad dressings, sauces, mayonnaise and even for cooking different foods, including frying and baking. This approach will help provide both consumers and the food industry with a variety of healthy and tasty foods.

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CHAPTER 4

Development and characterization of ice cream containing vegetable oils

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Abstract

Ice cream is considered one of the world's favorite desserts. It is important for consumers to get benefits and enjoyment from eating this sweet product. The main ingredients of ice cream are milk or cream, sugar, and sometimes egg yolks. Fruits, berries, cocoa, and vanilla are used to add flavor to the recipe. The milk or milk-egg mixture is first heated, then cooled, whipped to saturate the mass with air and obtain the appropriate texture, and frozen. Ice cream can be viewed as a multiphase system consisting of a cryo-concentrated aqueous phase, air bubbles, ice crystals and emulsified fat.

The fat in ice cream comes from the dairy ingredients, but vegetable fats such as coconut or palm oil can also be added. The fat phase ensures the optimal structure of the ice cream, gives it a rich flavor and influences the quality characteristics. It also helps to stabilize the foam, which contributes to the delicate creamy texture of the ice cream. The development of a blend of milk and vegetable fats is one of the most important factors in shaping the required texture, taste and aroma properties of ice cream. The use of liquid vegetable oils containing unsaturated fatty acids and vitamins makes it possible to create a new food product with health benefits.

The technology of ice cream using vegetable oils as an alternative to milk fats has been developed, which provides an innovative product enriched with unsaturated fatty acids. The influence of sunflower, linseed, and sesame oils on the texture of ice cream, its taste characteristics, and nutritional value was analyzed. The physicochemical properties of ice cream with the addition of vegetable oils, technological features of replacing milk fats with vegetable fats, as well as their impact on the stability of emulsions and organoleptic properties of the finished product are investigated. The technological aspects of the production of ice cream with vegetable oils, including emulsification, stabilization and freezing processes, are considered.

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The obtained results can be used to develop new types of ice cream with increased nutritional value and improved consumer characteristics.

Keywords

Ice cream, vegetable oils, texture, emulsion, sunflower oil, linseed oil, sesame oil, physicochemical properties, organoleptic properties, nutritional value, stabilization, freezing.

4.1 Relevance of developing a technology for the production of ice cream with the addition of vegetable oils

Ice cream is a popular multi-ingredient frozen dessert that includes dairy (milk, cream) or non-dairy ingredients, sugar, emulsifiers and stabilizers. It is the milk fat in classic ice cream that provides the delicate texture and mild flavor [1]. Depending on the composition, a distinction is made between traditional or classic dairy ice cream made from dairy products and alternative ice cream, in which milk fat is replaced by vegetable fats.

The fats in ice cream play an important role in shaping the texture – during low-temperature processing, fat crystals form a stable structure of the product, ensuring its creamy texture. The fat content slows down the melting process, thus ensuring the product's consumer appeal. The milk fat contained in whole milk is responsible for the excellent organoleptic characteristics of ice cream, giving it a creamy taste and flavor. On the other hand, milk fat balls distributed in the aqueous phase have different sizes, varying from 0.1 to 15 microns. At low temperatures, the fat crystals formed protrude from the surface of the fat globules, causing damage to their membrane, and fat globules aggregate. As a result, the stability of whole milk ice cream is significantly reduced [2].

Current global trends towards the consumption of "healthy" foods containing less saturated fatty acids are driving the search for a replacement for milk fat with vegetable oils. The use of vegetable oils in ice cream recipes can reduce calories, increase nutritional value and expand the range of products that can be consumed by vegans and lactose intolerant consumers. There have been studies on the use of soybean oil in ice cream, which has good emulsifying properties and provides a stable product structure. It has been found that replacing 40–50% of milk fat with soybean oil improves the stability of ice cream, as the apparent viscosity of the mixture increases due to a decrease in its particle size to 0.4–2 μm [3]. The combination of sunflower oil and extra virgin coconut oil reduces the melting rate of ice cream and ensures its stable structure [4]. Replacing milk fat with extra virgin coconut oil gives ice cream a delicate coconut flavor and aroma. However, the increased content of coconut oil reduces the resistance to melting [5]. The use of oleogels derived from

candelilla wax, hemp oil and olive oil in the production of plant-based ice cream allows to create a product with good physical, chemical and sensory properties [6]. Grape and pomegranate seeds and their oil, sesame seeds and sesame oil can be used to produce ice cream with prebiotic, phenolic and antioxidant properties [7]. When a mixture of hazelnut oil and olive oil is added to the ice cream recipe, the good physical and chemical properties of the ice cream are maintained, and some characteristics, such as melting speed, are improved. The addition of a blend of oils slows down the melting rate of ice cream [8]. On the other hand, although the use of vegetable oils has a number of advantages over milk fat, it should be borne in mind that not all vegetable oils are capable of providing the required texture of ice cream, and if the technology is not followed, they can lead to phase separation of the product.

Gelatin, a protein substance derived from animal collagen (skin, bones, membranes, etc.), is traditionally used in industrial ice cream production. Due to its functional properties, gelatin effectively acts as a gelling agent, thickener and stabilizer. The overall hardness of ice cream, its resistance to melting and organoleptic properties can be changed by changing the concentration of gelatin in the ice cream recipe [9].

In the light of the need to find environmentally and economically feasible alternatives to gelatin, there is a growing interest in natural hydrocolloids of plant origin. One of the most promising among them is galactomannan, a highly polymeric carbohydrate (polysaccharide) formed from mannose and galactose residues. Due to its properties, galactomannan effectively functions as a thickener, emulsion stabilizer, and potentially helps to reduce the permeability of toxic substances [10]. Depending on the galactose-mannan ratio, it is possible to distinguish between hay fenugreek gum, guar gum, tara gum and carob gum. Guar gum is derived from the seeds of the Cyamopsis tetragonal plant, known as guar. It is a natural polysaccharide that is highly soluble in water and can form a viscous gel even at low concentrations. A characteristic feature is that the addition of guar gum contributes to the formation of a viscous consistency of the product without heating, so it is well suited as a stabilizer for ice cream [10]. Guar gum provides a stable structure in a wide range of acidity – pH 4...10. In addition, guar gum is resistant to freezing and thawing.

4.2 Characteristics and chemical composition of oils

4.2.1 Sesame oil

Sesame oil is produced by pressing sesame seeds. Unrefined sesame oil is a viscous liquid of yellow-golden or amber color with a pleasant nutty flavor, while refined

sesame oil has a light-yellow color and a less intense flavor. Its advantage over other types of vegetable oils is its high antioxidant content, which extends its shelf life. Sesame oil contains the antioxidants sesamolin and sesamol, which help maintain cell integrity and healthy tissue function in the human body in the presence of oxidants [11]. The chemical composition of sesame oil is quite diverse. It contains fatty acids: saturated-palmitic – 7...10%, stearic – 4...6%, monounsaturated – oleic – 33...44% and polyunsaturated – linoleic – 40...50% and alpha-linolenic – 0.3...0.5%. In addition, sesame oil contains vitamin E, which has antioxidant and radioprotective effects and improves oxygen consumption by human tissues. 100 g of sesame oil contains 1.4 mg of vitamin E. Sesame oil phytosterols support healthy cholesterol [12]. Due to its properties, sesame oil is used in cooking and cosmetics.

4.2.2 Flaxseed oil

Flaxseed oil is obtained from flaxseeds by pressing them. In appearance, unrefined flaxseed oil is yellow with a greenish tint and is a rather viscous liquid with a specific bitter nutty and herbal flavor. A special feature of flaxseed oil is its ability to oxidize rapidly, which causes a change in taste. Refined flaxseed oil is a clear liquid with a less intense color and taste. Due to its beneficial properties, flaxseed oil is widely used in nutrition and medicine. The interest in using flaxseed oil is driven by its chemical composition. It contains saturated fatty acids: palmitic acid – 5%, stearic acid – 2...4%, monounsaturated oleic acid – 18%, and polyunsaturated alpha-linolenic acid – 50...60% and linoleic acid – 14...18%. The main value of flaxseed oil lies in its high content of alpha-linolenic fatty acid or omega-3. The ratio between omega-3 and omega-6 fatty acids in flaxseed oil is 4:1 [13]. Flaxseed oil is rich in vitamin E (tocopherols); 100 g of oil contains about 37 mg of vitamin E and tocopherols, which amount to 250 mg in 100 g of oil. In addition, flaxseed oil contains phytoestrogens or lignans, which are natural antioxidants [14].

4.2.3 Sunflower oil

Sunflower oil is obtained from sunflower seeds by pressing or extraction. Extra virgin sunflower oil has a deep yellow or amber color and a pleasant taste of roasted seeds. After refining, the oil becomes light yellow in color and has a neutral taste. The chemical composition of sunflower oil is slightly different from that of sesame and linseed oils. It contains saturated fatty acids: palmitic acid – 6%, stearic acid – 4%,

monounsaturated oleic acid – 20...40%, and polyunsaturated linoleic acid – up to 70%, and alpha-linolenic acid is almost absent. Sunflower oil is rich in vitamin E (tocopherols) and phytosterols. 100 g of sunflower oil contains 40...70 mg of vitamin E. In addition, sunflower oil contains lecithin [15]. The physicochemical properties of sunflower oil vary depending on its variety [16]. Sunflower oil is widely used in cooking.

A comparative description of vegetable oils is presented in **Table 4.1**.

Table 4.1 Comparative characteristics of oils

Characteristic	Type of oil		
	Sesame	Flaxseed	Sunflower
Color	Yellow-gold or amber	Yellow with a greenish tint	Yellow or amber
Flavor/aroma	Nutty, delicate	Bitter, nutty and herbal	Saturated seedy, refined neutral
Omega-3 content, %	0.5	50…60	Very low
Omega-6 content, %	40…50	14…18	48…74
Oleic acid, %	35…45	18	20…40
Saturated fatty acids, %	14	12	10…12
Vitamin E (tocopherols), mg/100 g	1.4	20	40…70
Other compounds	Sesamol, sesamin	Lignans, phytoestrogens	Lecithin, phytosterols

Source: compiled by the authors

4.3 Materials and methods

4.3.1 Materials and laboratory equipment

The developed soft ice cream compositions with the addition of vegetable oils, such as sesame oil, linseed oil and sunflower oil, were studied.

The following raw materials were used for the production of the ice cream prototypes:

– ultra-pasteurized cow's milk 3.2% – TM "Selyanske", Ukraine;
– white crystalline sugar – TM "Premiya", Ukraine;
– guar gum – TM "Zdorovo!", Ukraine;
– sunflower seeds – TM "Vyshyachanyi vkusok", Ukraine;
– sesame seeds – TM "WinWay", Ukraine;
– flax seeds – TM "Zdorovo!", Ukraine.

All raw materials were purchased at a local supermarket (Lutsk, Ukraine).

The following laboratory equipment was used in the study: oil press Dulong ZYJ06 600W; immersion blender Moulinex Quickchef DD 655D10; soft ice cream machine Klarstein Sweet Sundue; pH meter NS 0.00-14; pycnometer; drying cabinet DHG-9035A; thermometer Testo 405V1; laboratory scales FEN-V2003; microscope BRESSER Erudit Basic Mono. The study was conducted in the laboratory of Lutsk National Technical University (Ukraine).

4.3.2 Methods

4.3.2.1 Determination of ice cream melting and whipping resistance

The resistance to melting of the obtained experimental ice cream samples was determined according to the method [17]. The resistance to melting of all ice cream samples ranged from 81% to 83%.

The creaminess of ice cream samples was determined using the method described in [18].

To do this, the known volume of the mixture before making the ice cream and the ice cream itself after freezing was recorded, and then the defeat (*O*) was calculated using the formula

$$O\% = \frac{(V_2 - V_1)}{V_1} \cdot 100\%, \tag{4.1}$$

where *O*% – overrun of ice cream, %; V_1 – volume of the ice cream mixture before freezing, ml; V_2 – volume of ice cream after freezing, ml.

4.3.2.2 Determination of active acidity, solids content and density of ice cream

The active acidity of the ice cream mixture was investigated using a pH meter model NS 0.00-14 with a measuring range of 0.00–14.00 pH (with an error of ± 0.01 pH).

The determination of the mass fraction of dry substances in ice cream was carried out according to the standard method [19].

The density of the obtained ice cream samples is determined using a pycnometer according to the formula

$$\rho = m_1 - m_0 + \frac{A}{m_2} - m_0 + A \times 0.99823, \quad (4.2)$$

where ρ – density, g/cm^3; m_1, m_2 – respectively, the mass of the pycnometer with a mixture of ice cream and water, g; m_0 – mass of an empty pycnometer, g; 0.99823 – density of water at 20°C, g/cm^3; A – correction for aerostatic force.

The correction for the aerostatic force was calculated by the expression

$$A = 0.001204 \times V, \quad (4.3)$$

where 0.001204 – density of air at 20°C, g/cm^3; V – capacity of the pycnometer, g.

4.3.2.3 Determination of the crystal structure and the number of air bubbles in the ice cream samples

Microscopic examination of the samples was carried out using a light microscope at a magnification of 7 × 15.

For the analysis, a small amount of ice cream was applied to the graduation grid of the Goryaev chamber, covered with a cover glass and immediately placed under the microscope. During sample preparation, ice crystals melt, but the foam remains unchanged and its structure is clearly visible. In such conditions, moisture evaporation is almost non-existent, so the shells of air bubbles remain unchanged. The air bubbles were observed in transmitted light immediately after the preparation of the samples.

4.3.2.4 Determining the firmness of foam

The firmness of foam is determined by the height of its column. Stir 100 g of ice cream into a 50 mm diameter beaker. Melt it at room temperature, which should reach 20°C. The height of the foam column is measured at the beginning of the study, and then every 5, 10, 15, 20, 30, 40 minutes, and the result is recorded. The calculation is performed using the following formula

$$\text{Foam stability (\%)} = \frac{h_1}{h_0} \cdot 100, \quad (4.4)$$

where h_0 – height of the foam column after a certain time, mm; h_1 – initial height of the ice cream scoop, mm.

4.3.2.5 Statistical analysis and calculations

All data are presented as mean ± standard deviation (SD). Statistical analysis and calculations were performed using Mathcad 14 software.

4.4 Technological process of producing ice cream with vegetable oils

The quality of ice cream is determined not only by the organoleptic properties, which are determined by the composition of the raw materials, but also by its structural and rheological characteristics. The structure of the product depends mainly on the size of the ice crystals: the smaller and more evenly distributed these crystals are, the higher the quality of the ice cream. Consistency, which describes the mechanical properties of the product, reflects parameters such as hardness, softness and density and is an important indicator of consumer value. A sample of high-quality ice cream should form a homogeneous liquid, similar in texture to heavy cream, when it melts.

Dairy ice cream recipes use milk (regular or dry) of different fat content, as well as fats of both animal and vegetable origin. This study focuses on the effect of the concentration of vegetable oils on the rheological properties of ice cream. Determining the type of these components, which depends on the recipe, significantly affects the rheological characteristics and organoleptic properties of the product. Optimization of the composition is an urgent task, as it helps to reduce the cost of products without significantly affecting their consumer characteristics.

Ice cream is a high-calorie dessert due to its high fat and sugar content. From a nutritional perspective, this can have undesirable consequences, so it is important to use alternative ingredients that reduce the calorie content of the finished product. For example, the use of lactose-free milk allows to create ice cream for consumers with lactose intolerance. In addition, the replacement of animal fats with vegetable fats helps to reduce cholesterol, lower the calorie content of the product and extend its shelf life.

The presence of free fat in ice cream is important for creating high-quality ice cream. The presence of free fat determines the 'creaminess' and 'fat content' of ice cream. An increase of more than 30% leads to coalescence, which is manifested in such a defect as 'coarseness', and with less than 10% free fat in ice cream, it is difficult to achieve a high whipping index and high taste of the product. When selecting vegetable fats as a partial replacement for milk fats, recommendations on the composition of fat fractions, the ratio of saturated and unsaturated fatty acids, crystallization and solidification parameters were taken into account (see recipes in **Table 4.2**).

Based on the random selection method, three formulations containing sunflower, sesame and linseed oils were calculated.

The essence of the random selection method is as follows: knowing the raw materials used in the recipe, the weight of one or more components is randomly set. The calculations were based on the amount of added fat, skimmed milk powder residue (SMPR), solids and sucrose (**Table 4.2**).

Table 4.2 Mass fraction of recipe components in model ice cream compositions

Prescription component, g	MC No. 1 (flax)	MC No. 2 (sesame)	MC No. 3 (sunflower)
Cow's milk, 3.2%	77.18	77.18	77.18
Flaxseed oil	8.58	–	–
Sesame oil	–	8.58	–
Sunflower oil	–	–	858
Guar gum	0.51	0.51	0.51
White crystalline sugar	13.73	13.73	13.73
Output, g	100	100	100

Source: compiled by the authors

Each of the formulations contains a certain amount of vegetable oil, namely:

1) recipe No. 1 – 50 g of linseed oil (**Fig. 4.1, *a***);
2) recipe No. 2 – 50 g of sesame oil (**Fig. 4.1, *b***);
3) recipe No. 3 – 50 g of sunflower oil (**Fig. 4.1, *c***).

a *b* *c*

Fig. 4.1 Appearance of the experimental samples of ice cream with the addition of vegetable oils: *a* – MC No. 1 with the addition of flaxseed oil; *b* – MC No. 2 with the addition of sesame oil; *c* – MC No. 3 with the addition of sunflower oil
Source: compiled by the authors

Standard physical, chemical and organoleptic methods were used in the study. The same set of products and the same amount of vegetable oils were used for all recipes.

Ice cream technologies with the addition of vegetable oils differ from the classical technological scheme by an additional operation – emulsification of the mixture (**Fig. 4.2**).

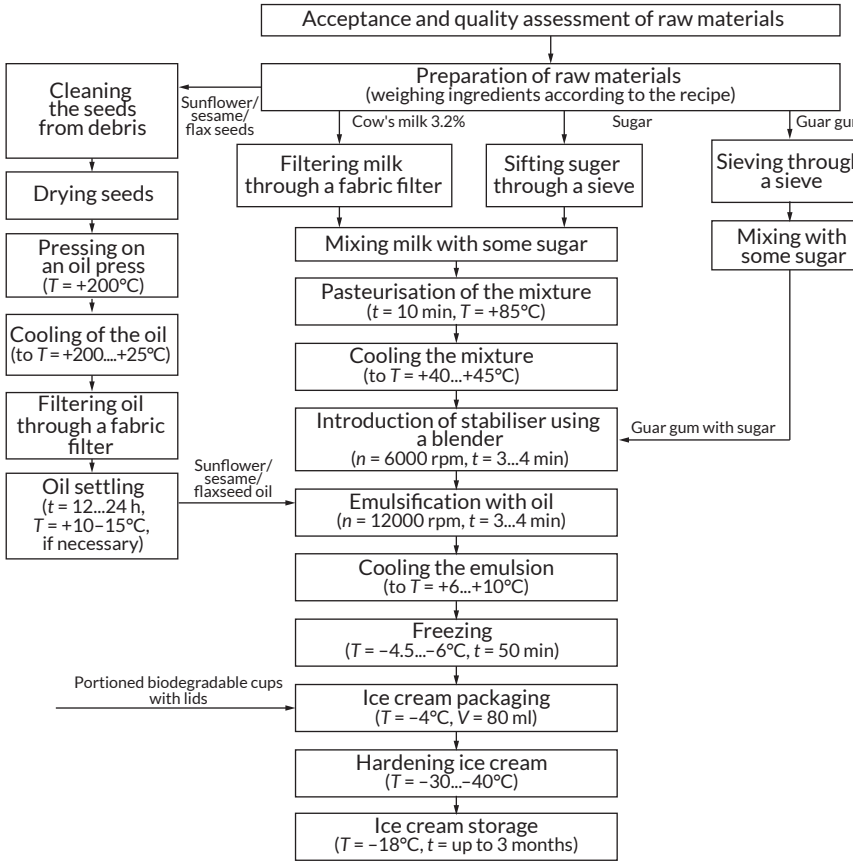


Fig. 4.2 Flow chart of ice cream production with the addition of vegetable oils
Source: compiled by the authors

To do this, part of the sugar is added to the milk and heated to a temperature of 40–45°C, then guar gum mixed with the rest of the sugar is added in small portions with constant stirring using an immersion blender. After that, the mixture becomes thicker, similar to natural drinking yoghurt. Next, the speed is increased and the oil (sunflower/ flax/sesame) is added in a thin stream. These processes create an emulsion mixture.

For the production of prototypes of the finished product, the oil was obtained by pressing on an oil press Dulong ZYJ06 600W (country of origin: China), which is an environmentally friendly method of producing natural oil without the use of chemical solvents.

To make the ice cream, the oil yield from a certain amount of sunflower, flax and sesame seeds was taken into account. The yield depends on many factors, including the type, fat content, seed moisture, efficiency and capacity of the oil press, etc. Estimated oil yields for sunflower are 35–50%, flax – 30–40%, and sesame – 45–55%.

A comparative characterization was carried out for all quality indicators of ice cream produced according to the traditional recipe of liquid milk mixture and ice cream made with the addition of vegetable oils.

A tasting group of experts (TG) was involved in the organoleptic evaluation of the ice cream samples. The expert panel evaluated the ice cream on a 5-point scale, where 1 is an unsatisfactory rating and 5 is an excellent rating.

The quality indicators of the product were determined in the following sequence: appearance (consistency); color of the finished product and the appearance of the pattern on the cut; taste and smell (aroma).

The overall quality score of the sample is calculated as the arithmetic mean of the scores of the members of the Panel participating in the evaluation to the first decimal place. The average score for the ice cream indicators is shown in **Fig. 4.3**.

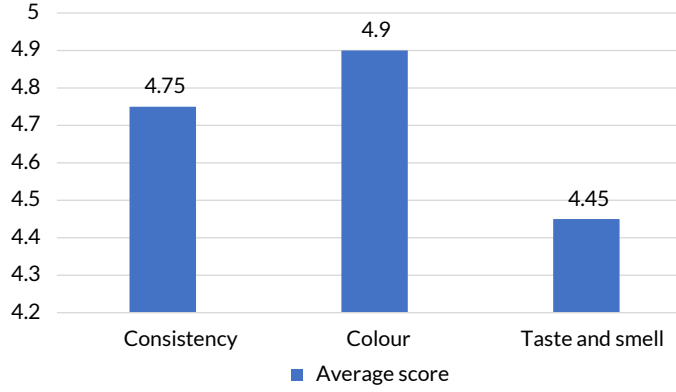


Fig. 4.3 Scoring of organoleptic characteristics of ice cream
Source: compiled by the authors

The resulting samples were tested for whipping (%) and foam stability and resistance to melting. The results are shown in **Fig. 4.4–4.6**.

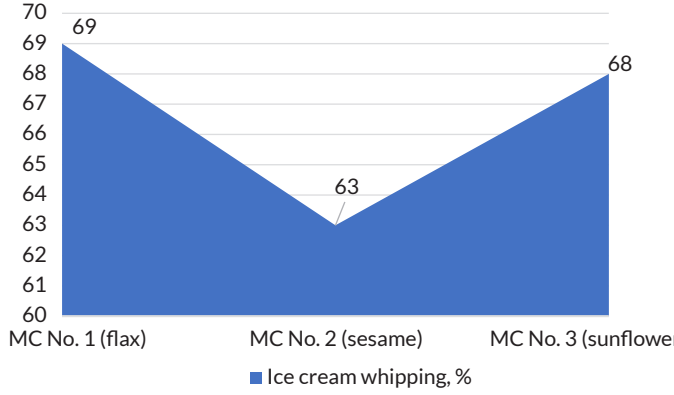


Fig. 4.4 Ice cream samples' whipping, %
Source: compiled by the authors

Thus, the defect rate of the experimental samples was in the range of 63–69%. At the same time, the use of vegetable oils leads to an increase in whipping, and therefore the quality of the finished product.

Due to the partially agglomerated fat adsorbed on the surface of air bubbles formed during the freezing process, the experimental samples achieved a high rate of whipping, which indicates a high ability of the mixture to be saturated with air.

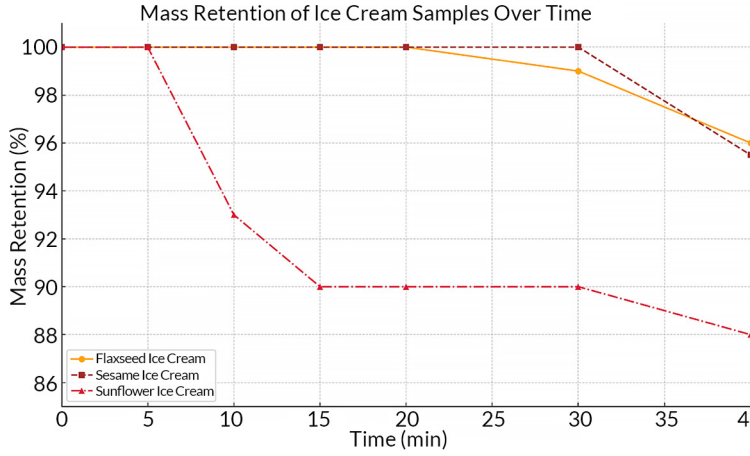


Fig. 4.5 Dynamics of changes in the height of the measuring cylinder column when determining the stability of ice cream foam

Resistance to melting is, first of all, very important for maintaining high organoleptic characteristics of ice cream, because when it leaves the freezer, it has a high temperature (**Fig. 4.6**).

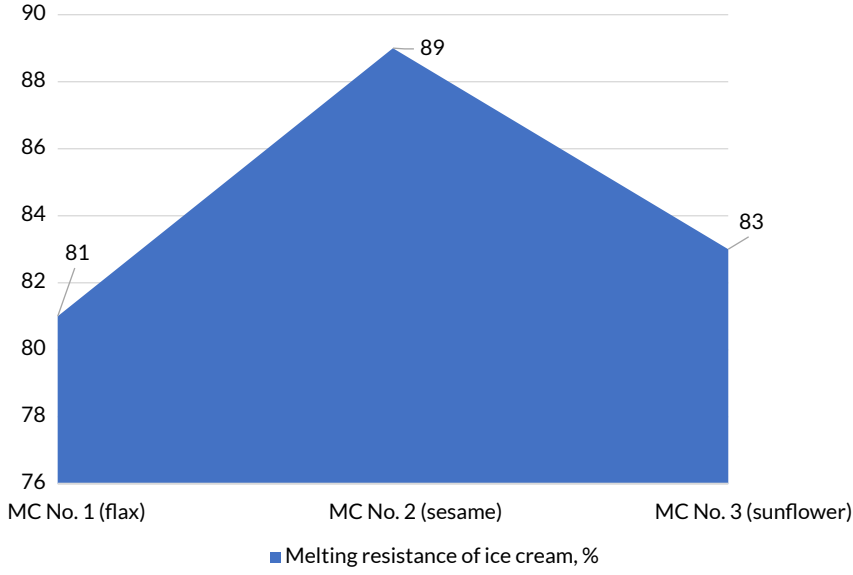


Fig. 4.6 Melting resistance of ice cream samples, %
Source: compiled by the authors

In addition to the above, the quality of soft ice cream was compared based on the density and the resulting crystalline structure of the final product after freezing.

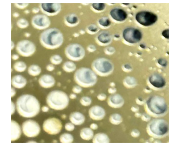
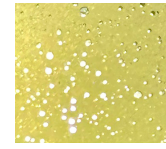
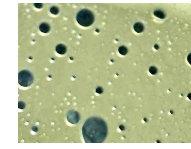
The results of the conducted research are presented in **Table 4.3**.

A comparative analysis of the overrun indicators of soft ice cream made with the addition of various vegetable oils shows that the use of liquid vegetable oil does not lead to a decrease in the overrun of the final product. Thus, the incorporation of vegetable oils into the formulations of liquid mixtures for soft ice cream ensures the production of a product with improved sensory characteristics and physicochemical properties.

According to the results of the sensory evaluation, it was established that the experimental ice cream samples demonstrated characteristic differences in taste, color, and aroma. Considering this, flaxseed, sesame, and sunflower oils can be recommended as additional raw materials for ice cream production. Their use offers the

potential to enrich the product with valuable nutrients without significantly affecting its sensory characteristics.

Table 4.3 Organoleptic and physicochemical characteristics of model ice cream compositions

Parameter	Model ice cream compositions		
	MC No. 1 (flax)	MC No. 2 (sesame)	MC No. 3 (sunflower)
Consistency	Homogeneous, whipped, without organoleptically perceptible lumps of the stabilizer, good foam stability		
Color	Homogeneous throughout the mass. Even from milky to yellowish-cream		
Taste and smell	Clean, characteristic of the given type of mixture and the raw materials used		
Mass fraction of dry substances, %, not less than	29.4	29.8	29.6
Density, kg/m^3	914.7 ± 0.2	1021.3 ± 0.3	965.9 ± 0.5
Active acidity, pH units	6.5 ± 0.05	6.5 ± 0.05	6.6 ± 0.05
Melting resistance, %	81	89	83
Whipping, %	69	63	68
Crystalline structure of ice cream			

Source: compiled by the authors

4.5 Evaluation of the biological and nutritional value of ice cream samples with the addition of vegetable oils

The fat content in ice cream is significant: it determines the structure, consistency, taste preferences, and the technological properties of the mixture during maturation and freezing.

Compared to animal fats, vegetable oils have several advantages as a partial substitute for milk fat: they are cholesterol-free, are an important source of vitamins, and contain unsaturated fatty acids that help reduce cholesterol levels in the body.

About 8% of the total fatty acids in milk fat consist of specific low-molecular volatile fatty acids (butyric, caproic, and caprylic acids). Polyunsaturated fatty acids,

which have high biological activity, are present in milk fat in relatively small amounts: linoleic acid – 3–5%, linolenic and arachidonic acids – about 1%.

To compare the fatty acid composition in milk fat and vegetable oils as substitutes for milk fat, the content of polyunsaturated fatty acids (PUFAs) in ice cream with the addition of flax, sesame, and sunflower oils was theoretically calculated and compared to traditional dairy ice cream, as shown in **Table 4.4**. It is assumed that ice cream would be better sold in packaging of 75 g.

Table 4.4 Content of polyunsaturated fatty acids (PUFAs) in ice cream

	MC No. 1 (flax)	MC No. 2 (sesame)	MC No. 3 (sunflower)	Traditional dairy ice cream	Daily requirement, g
PUFAs, g	3.070	2.985	2.560	0.675	13

Based on the calculation results, conclusions were made that significant results were achieved in the content of polyunsaturated fatty acids (about 20% of the daily requirement).

Thus, the developed ice cream with the use of vegetable oils, specifically flax, sesame, and sunflower oils, has allowed for the creation of a new, physiologically valuable product, which surpasses traditional ice cream in PUFA content and provides the final product with functional properties.

When considering the developed ice cream from the perspective of preventive-dietary nutrition, one cannot overlook the energy value (calorific value) and the nutritional value of the final product. **Table 4.5** presents a comparative analysis of the nutritional and energy value of ice cream with the addition of vegetable oils and traditional ice cream.

Table 4.5 Nutritional and energy value of ice cream with the addition of vegetable oils and traditional dairy ice cream with milk fat

Content of substances per 100 g	Ice cream with the addition of vegetable oils	Traditional dairy ice cream
Fats, g	4–5	15
Proteins, g	3–3.5	4
Carbohydrates, g	20–23	19.5
Calorific value, kcal	150–160	229

Based on these data, it can be concluded that the calorific value of ice cream with the addition of vegetable oils is slightly lower than that of traditional dairy ice cream.

4.6 Conclusions

The advantages of using vegetable oils as a partial replacement for milk fat to provide ice cream with functional properties were studied.

The fatty acid composition of milk fat determines the characteristics of its texture in the final product. Milk fat is unstable to the effects of high temperatures, light, water vapor, oxygen in the air, and solutions of alkalis and acids. Under the influence of these factors, it hydrolyses, oxidizes, and becomes rancid, making it unstable during storage. Milk fat, on the other hand, is resistant to low temperatures and, if stored properly, its quality indicators do not change significantly. However, the disadvantage of products with a high milk fat content, such as ice cream, is the high cholesterol content with a high level of saturated fatty acids (up to 65%) and a low level of polyunsaturated fatty acids (no more than 4%).

Compared to animal fats, vegetable oils offer several advantages as substitutes for milk fat: they are cholesterol-free, serve as an important source of vitamins, and contain unsaturated fatty acids, which help remove cholesterol from the body.

Replacing milk fat in dietary nutrition has also proven beneficial due to the following advantages:

– ease of use;
– resistance to temperature fluctuations and bacterial spoilage;
– possibility of selecting fats according to religious dietary requirements;
– ability to regulate nutritional value.

However, not all vegetable oils are resistant to high and low temperatures. This property is determined by its type, fatty acid composition and degree of purification. Flaxseed oil is the least resistant, as it is capable of oxidation at low temperatures. Therefore, ice cream with flaxseed oil has a short shelf life. Sesame oil, due to its high content of oleic acid, practically does not change its quality when exposed to low temperatures and is resistant to cold. Ice cream with a partial replacement of milk fat with sesame oil has a long shelf life without reducing its quality. Sunflower oil is relatively stable at low temperatures, so if milk fat is partially replaced with sunflower oil, the ice cream will retain its quality characteristics.

Therefore, by applying vegetable oils, ice cream can become not only a delicious dessert but also a healthy one.

The use of new ingredients not only allows for greater variety in ice cream recipes but also helps to reduce caloric content and improve the economic performance of production.

Thus, the use of liquid vegetable oils is a promising approach for creating a product with improved consumer properties and competitiveness in the market.

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CHAPTER 5

Compositional analysis and potential of buckwheat and oats as functional food ingredients

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Olha Hulai

Abstract

Buckwheat and oats are traditional, though not the most popular, crops with strong environmental adaptability. The bioactive substances in buckwheat and oats have a positive impact on human health, including antioxidant and anti-inflammatory properties and the ability to prevent cancer. In this work, a comprehensive analysis of buckwheat and oat powders was carried out, including sieve analysis, infrared spectroscopy (IR spectroscopy), X-ray fluorescence analysis (XRF) and gas chromatography with mass spectrometry (GC/MS).

According to the results of sieve analysis, the highest content of fractions with a particle diameter of 1.1–0.5 mm was found: 41.76% for buckwheat powder and 52.56% for oat powder. The analysis of the IR spectra showed a similar chemical composition of both samples, including carbohydrates, proteins, fats and minerals. However, the buckwheat powder had a higher content of proteins and carbonyl compounds, and the oat powder had a higher content of polysaccharides. X-ray fluorescence analysis showed that both samples contain mainly C, H, P, S, K, Ca, Mn, Fe, Cu, Zn, but in different proportions. Buckwheat powder is characterized by a higher content of potassium and phosphorus, while oat powder has higher levels of calcium and manganese.

The GC/MS method was used to identify 15 bioactive compounds in buckwheat powder and 18 in oat powder. Sucrose, palmitic acid, linoleic acid and phytosterols (gamma-sitosterol, campesterol) were found in both samples. Buckwheat powder has a higher content of antioxidants, in particular γ-tocopherol, while oat powder contains steroidal compounds and oxazole derivatives that may affect lipid metabolism.

The study confirmed the unique nutritional profile of buckwheat and oat groats grown in Volyn. The results can be used in the field of functional food, pharmacology and nutrition to develop products with high biological activity.

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Keywords
Buckwheat, oats, nutrient, chemical composition, functional food, antioxidants, bioactive compounds, GC-MS, XRF.

5.1 Introduction

In the context of current demographic trends, in particular the growth of the world's population by about 1.1% per year (according to the United Nations in 2019), ensuring global food security remains an extremely urgent issue [1, 2]. The modern agricultural industry prefers monoculture cultivation of a limited set of crops [3]. This strategy leads to a narrowing of the range of available nutrients for consumers, as the human diet is based on a small number of plant species [4].

According to researchers [5], 67% of humanity's energy intake comes from four main crops: wheat, rice, corn and soybeans. The dominance of these crops in global agriculture creates global patterns of consumption. Despite the undoubted nutritional value of the aforementioned crops, numerous studies demonstrate their insufficiency in providing the full range of essential nutrients critical for the optimal functioning of the human body [6]. In particular, there is a significant deficiency of essential micronutrients, proteins, essential amino acids and vitamins, which are fundamental components of a balanced diet. This nutritional deficiency can lead to long-term health consequences for the population, including an increased risk of developing chronic diseases and a reduced overall quality of life. In addition, due to global climate change, global production of major consumer crops may decline significantly [7].

Buckwheat and oats are traditional crops grown around the world. It should be noted that these crops have a strong environmental adaptability that allows them to grow in almost all types of extreme environments. In 2023, the global production of buckwheat was 2.2 million tons, and oats 18.8 million tons [8]. The dynamics of changes in buckwheat and oat production and area over the past 5 years are shown in the diagram (**Fig. 5.1**). The main producers of buckwheat grain in 2023 were Russia, China and Ukraine (**Table 5.1**). Russia, Canada and Australia produce the most oats in the world. The level of production of these crops is significantly lower compared to wheat, rice, corn and soybeans.

At the same time, oats and buckwheat have a unique nutritional profile and potentially significant health benefits, which underscores the need to increase the diversity of agricultural production and diets to improve global health and food security.

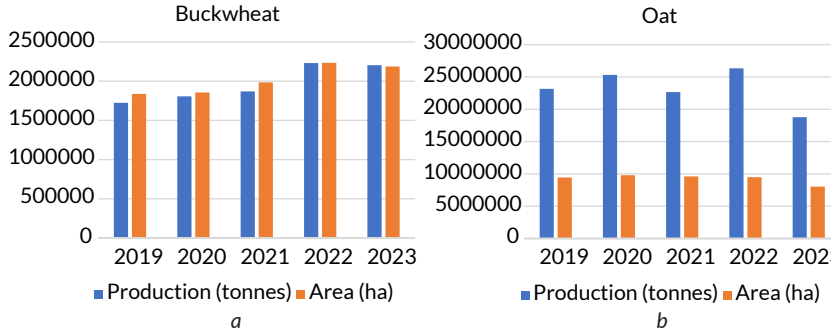

Fig. 5.1 Dynamics of changes in buckwheat (*a*) and oat (*b*) production and sown area
Source: [8]

Table 5.1 World's largest producers of buckwheat and oat (production year 2023)

Buckwheat			Oats		
Countries	**Production (tons)**	**Area (ha)**	**Countries**	**Production (tons)**	**Area (ha)**
Russian Federation	1149066.65	1037110	Russian Federation	3300000	1770000
China	504265.75	624246	Canada	2635574	822500
Ukraine	210720.00	147900	Poland	1503440	497690
USA	86679.82	83462	Finland	1019720	291300
Kazakhstan	83491.29	114484	Australia	959829	569082
Brazil	64611.39	47490	Brazil	907046	528649
Japan	35500.00	66700	Great Britain	830000	167000
Tanzania	22190.89	21218	USA	828010	336300
Belarus	16937.05	15593	China	600000	160511
Nepal	15083.49	11857	Spain	464140	464760
World total	2204015	2187456	World total	18776760	8024447

Source: [8]

The aim of the presented study is:

1) to analyze the literature data on the biochemical characteristics of buckwheat and oats as important components of functional food;

2) to experimentally determine the content of the main micro and macronutrients in powders obtained from buckwheat and oat grains grown in the Volyn region (Ukraine).

5.2 Chemical composition and biochemical activity of buckwheat and oat grains

5.2.1 Buckwheat

Buckwheat grain contains a balanced complex of macro- and microelements, as well as a wide range of biologically active phytocompounds. Epidemiological and clinical studies show that regular consumption of this grain is associated with significant preventive effects against a number of chronic non-communicable diseases. In particular, there is a reduced risk of developing cancer, metabolic syndrome (including obesity and type 2 diabetes), and cardiovascular disease [9].

Among all the buckwheat species, only two are grown for food grain production: common buckwheat (*Fagopyrum esculentum Moench*) and Tatar buckwheat (*F. tataricum(L.)Gaertn*).Commonbuckwheatiswidespread inAsia,Europe,AmericaandAustria, while the cultivation area of tartaric buckwheat is limited to the Asian region [10].

There are two groups of buckwheat seed dishes: flour and cereals. Other buckwheat products include buckwheat honey, green buckwheat tea, buckwheat sprouts and fresh green parts of the plant used as salad.

Buckwheat grain is a valuable source of protein, starch, fat, dietary fiber, minerals, vitamins and phytocompounds [11]. **Table 5.2** shows the content of the main components in different parts of buckwheat grain [11].

Table 5.2 Main chemical composition of whole buckwheat seeds, dehulled seeds and husks

Sample	Protein ($g \cdot 100g^{-1}$)	Fat ($g \cdot 100g^{-1}$)	Total carbohydrates ($g \cdot 100g^{-1}$)	Starch ($g \cdot 100g^{-1}$)
Dehulled seed	15.29–19.96	2.19–2.48	78.18–79.68	45.24–55.11
Whole seed	12.28–15.61	1.72–2.24	77.36–81.38	38.41–43.11
Hull	5.13–5.68	0.50–0.81	91.72–92.19	0.31–2.26

Source: [11]

Buckwheat is an important source of protein, as the average protein content in its grain can reach 8.5–18.8% [12]. Buckwheat proteins have one of the highest levels of amino acids among vegetable proteins. Buckwheat proteins are well balanced and contain albumin, globulins, prolamins and glutelins and provide the human body with such important amino acids as leucine, phenylalanine, lysine, threonine, isoleucine, asparagine and cysteine [13]. The peculiarity of buckwheat's protein composition is the absence of gluten, which allows expanding the food base for people with gluten

intolerance and celiac disease [14]. Acting similarly to dietary fiber, buckwheat proteins prevent obesity. They have special biological activity in reducing cholesterol and blood pressure.

Work [15] notes that the presence of tannins in buckwheat can lead to a decrease in protein absorption in humans and animals due to their ability to form stable complexes with plant proteins. Tannins form numerous bonds with protein molecules, which disrupts their metabolic activity and nutrient availability. However, the presence of the amino acid lysine in buckwheat increases the digestibility of proteins compared to other cereals.

The total carbohydrate content of buckwheat grain is about 80%. The main carbohydrate in this raw material is starch, with an average content of 54.5% [16]. Buckwheat grain contains 18 different fatty acids with a total content of 1.5–3.7%. The most common higher carboxylic acids are palmitic, oleic and linoleic, which account for about 88% of the total content of these substances [15].

The nutritional potential of buckwheat is significantly increased by the presence of biologically active substances of polyphenolic compounds (bioactive peptides, flavonoids and phenolic acids) [12]. The content of the main biologically active substances is presented in **Table 5.3** [11]. Buckwheat contains a significant amount of flavonoids such as rutin, isoorientin, quercetin, isovitexin, vitexin and orientin. Buckwheat grain is the richest source of rutin and quercetin among pseudocereals (maximum 5.186 mg/100 g and 857.625 mg/100 g, respectively) [12, 17], which is 10–100 times higher than in other plants. Buckwheat flavonoids are contained in the grain hull [11]. Bioactive substances have a positive effect on human health, in particular, they exhibit antioxidant and anti-inflammatory properties and are able to prevent cancer [18].

Table 5.3 Bioactive compounds of whole buckwheat seeds, dehulled seeds and husks

Sample	Dietary fiber ($g \cdot 100g^{-1}$)	Resistant starch ($g \cdot 100g^{-1}$)	Total polyphenols ($mg \cdot 100g^{-1}$)	Antioxidant activity ($mmol\ Trolox \cdot g^{-1}$)
Dehulled seed	1.16–6.65	6.13–11.35	280.00–328.03	63.20–66.50
Whole seed	20.32–25.45	3.29–5.64	311.98–357.14	31.28–34.93
Hull	76.52–80.73	not found	434.06–525.45	42.93–49.05

Source: [11]

Buckwheat grain contains a variety of minerals and vitamins. The concentration of the main macronutrients phosphorus (P), potassium (K), magnesium (Mg) and calcium (Ca) is over 100 mg per kilogram of dry weight. The content of micronutrients

is significantly lower than that of macronutrients, but the concentrations of iron (Fe), manganese (Mn) and zinc (Zn) are higher than other micronutrients [15]. Vitamins A, C, E and B vitamins are found in buckwheat. The average vitamin C content is 5 mg/100 g in grain, and its content in buckwheat sprouts is 5 times higher (25 mg/100 g).

5.2.2 Oats

Coated oats (*Avena sativa L.*) and naked oats (*Avena nuda*) are among the most valuable cereal crops in the world due to the optimal organoleptic properties of the grain and its ability to stimulate metabolic processes in the body [18]. Oat grain is an important source of carbohydrates, dietary soluble fiber, balanced protein, lipids, various phenolic compounds, vitamins and minerals. The basic chemical composition of different types of oat grains is shown in **Table 5.4** [19].

Oat grain stands out among other cereal crops due to its high protein content (mainly globulin fraction) of 7.4 to 14.9% of dry weight [19]. Proteins extracted from oatmeal are characterized by a high degree of digestibility (90.3–94.2% of dry weight) and significant biological value (74.5–79.6% of dry weight), which indicates their significant nutritional value.

Table 5.4 Main chemical composition of whole oats seeds, dehulled oats seeds, naked oat and husks

Sample	Protein ($g \cdot 100g^{-1}$)	Fat ($g \cdot 100g^{-1}$)	Total carbohydrates ($g \cdot 100g^{-1}$)	Starch ($g \cdot 100g^{-1}$)
Dehulled seed	12.93–14.86	4.33–7.64	62.03–69.80	48.08–49.17
Whole seed	9.91–10.95	1.72–2.24	53.02–65.81	57.92–64.21
Naked oat	11.91–13.62	7.53–9.51	70.11–72.14	31.55–35.27
Hull	1.42–7.40	0.50–1.51	63.32–82.74	2.52–16.33

Source: [19]

The amino acid composition of oat grain is quite diverse compared to other cereals, and the concentration of essential amino acids (lysine, methionine, threonine, tyrosine, leucine, valine, and phenylalanine) is higher [19]. Oats do not contain gluten. Studies show that people with celiac disease can consume foods containing oat protein. While most celiac patients tolerate oats, a small proportion may be sensitive because they react to avenin, an oat protein that is structurally similar to gluten.

The starch content of oat grain is lower than that of other cereals (30–60%) [19, 20]. In addition, oat starch has a small granule size, higher amylose content, high viscosity and high water retention capacity. Due to these characteristics, oats are widely used in the food industry as a thickener and gelling agent.

The content of the main bioactive substances is presented in **Table 5.5** according to [21]. The content of higher carboxylic acids in oat grain is 2.2–11%. Unsaturated higher carboxylic acids make up 80% of all fatty acids present in oat grain. The most common are linoleic oleic, docosahexaenoic, eicosapentaenoic and arachidonic. Among the saturated higher carboxylic acids, palmitic acid prevails with a content of 21.4–22.7% of the total amount of higher fatty acids in oat grain.

Table 5.5 Bioactive compounds of whole oats seeds, dehulled oats seeds, naked oat and husks

Sample	Dietary fiber ($g \cdot 100g^{-1}$)	β-glucan ($g \cdot 100g^{-1}$)	Total polyphenols ($mg \cdot 100g^{-1}$)
Dehulled seed	1.16–6.65	4.31–5.1	20.9–29.7
Whole seed	20.12–38.20	2.70–3.54	23.8–29.8
Naked oat	8.6–12.11	3.92–4.64	10.2–18.2
Hull	70.16–71.33	0.003–0.006	19.3–30.6

Source: [21]

Oats have a high content of soluble dietary fiber, in particular β-glucans, which make up 3% to 5% of the dry weight of the grain. Numerous scientific studies have shown that β-glucans have a pronounced hypolipidemic activity, helping to reduce the level of total cholesterol and low-density lipoprotein in the blood. In addition, due to their ability to slow down the breakdown and absorption of carbohydrates, β-glucans effectively stabilize blood glucose levels, making them useful for the prevention and treatment of diabetes. Recent scientific studies have also pointed to the anti-cancer and anti-inflammatory properties of β-glucans, which may be related to their immunomodulatory activity [22].

Oat grain is an important source of many minerals essential for human health. All the main macro- and microelements are present in the grain of this crop, including Ca, Mg, Fe, Mn, Cu, Zn, P and K. The high content of phosphorus and potassium, more than 300 mg/100 g, makes oat products a valuable source of minerals in the diet [23]. Oatmeal is rich in B vitamins (B1, B2, B3 and B5) [24]. In addition, oat products also contain vitamin E, which has high antioxidant properties. The spectrum of biologically active polyphenolic compounds in oats is similar to buckwheat, but the content of these compounds, in particular rutin and quercetin, is significantly lower (maximum 0.48 mg/100 g and 8.9 mg/100 g, respectively) than in oats [12].

5.3 Materials and methods

For the study, samples of buckwheat and oat groats produced by Zemledar-Info LLC were selected. To obtain buckwheat and oat powders, the respective cereals were ground using a BOSCH TSM6A013B coffee grinder. The bulk density of the crushed oat and buckwheat raw materials was determined as the ratio of the weight of the raw material to its volume.

The fractional content of the studied powders by size was determined by sieve analysis. The essence of the analysis is the mechanical distribution of particles by size [25]. The test material (50 g) was sieved through a set of sieves of different mesh diameters. The percentage of each fraction (*A*) was calculated by the formula

$$A = \frac{m_i}{m} \times 100,$$

where m_i – the mass of the *i*-th fraction, *m* – the total mass of the mixture.

The average particle size $\overline{d_i}$ of the i-th fraction was calculated as the arithmetic mean between the hole sizes d_j of the sieve on which the fraction was retained and the hole sizes d_{j-1} of the previous sieve

$$\overline{d_i} = 0.5\left(d_j + d_{j+1}\right),$$

where $\overline{d_i}$ – the average particle size of the *i*-th fraction, mm; d_j – the diameter of the holes of the lower sieve, mm; d_{j-1} – the diameter of the holes of the upper sieve, mm. At least 3 sievings of samples of the same weight were carried out, and the results of the fraction with a relative deviation from the mean value of no more than 5% were taken into account.

The infrared (IR) spectra were recorded using an IRAffinity-1S spectrophotometer (Japan) in the frequency range of 4000–400 cm^{-1} using the single-beam method in reflected light. The material under study was mixed in an agate mortar with KBr powder. Then, samples were formed on a hydraulic press with a force of 20 MPa in the ratio: test material –1 mg, KBr – 300 mg. A Nicolet iS10 FT-IR spectrometer was used to determine the functional composition of the samples.

The relative content of chemical elements in the raw material samples was determined using confocal micro-X-ray fluorescence spectroscopy (high-performance micro-X-ray fluorescence (μ-XRF) spectrometer M4 TORNADO). The conditions of the study are shown in **Table 5.6**.

Table 5.6 Conditions for XRD analysis

Parameter	Value	Unit
Real-time	42,908	ms
Live-time	30,000	ms
Detector type	XFlash 430	–
Si sead layer	0.029	μm
Detector thickness	0.45	mm
Window type	Custom type	–
Fano factor	0.114	–
Mn FWHM	142.43	eV
Calibration (linear)	10	eV
Calibration (absolute)	–955.9	eV
Channels	4095	–

In order to confirm the qualitative composition of buckwheat and oat powders, a study was conducted by gas chromatography with mass spectrometry (GC/MS) [26]. For the analysis, 0.6 g of the respective powders were placed in tubes with 5 ml of CH_3OH, extracted in an ultrasonic washer for 30 min (ultrasonic washer "WUC-A02H"), then centrifuged for 5 min (centrifuge laboratory "80-1"), and the extract was taken and analyzed under the conditions given in **Table 5.7**. Identical measurement results were obtained for three samples of each material, and the accuracy of the measurements corresponds to the technical characteristics of the equipment used.

Table 5.7 Conditions of the study by chromatography-mass spectrometry

Parameter	Value	Unit
1	2	3
Column type	Rxi®-5ms	–
Column dimensions	30 m × 0.25 mm × 0.25 μm	–
Carrier gas	Helium	–
Carrier gas flow rate	1.18	ml/min (constant flow)
Oven temperature program	**Start:** 80°C (hold 1 min)	°C
	Ramp: 15°C/min to 250°C (hold 8 min)	°C/min
	Ramp: 20°C/min to 310°C (hold 10 min)	°C/min
Injection mode	Autosampler AOC-20i+s	–

Continuation of Table 5.7

1	2	3
Split ratio	20:1	–
Injection volume	1	μl
Detector type	MSD QP2020NX EI	–
Operation mode	Scan, range 40–900 amu	–
Solvent delay	2.5	min
Multiplier voltage	According to tuning file	–
Ion source temperature	250	°C
Injector temperature	250	°C
Interface temperature	300	°C
Control substance	Methanol	–

The study was conducted in the laboratory of the Lutsk National Technical University (Ukraine). The micro-X-ray fluorescence spectroscopy study was conducted in the laboratory of the Institute of Analytical Chemistry at TU Bergakademie Freiberg as part of the international educational project "SUUUpoRT – Structural support of Ukrainian Universities in Upkeep and Rebuilding of Higher Education".

5.4 Results of experimental studies

The results of the sieve analysis of buckwheat and oat powders are shown in **Table 5.8**. The differential curves of the particle size distribution of the powders are shown in **Fig. 5.2**. According to the results of sieve analysis, the highest content of fractions with a particle diameter of 1.1 to 0.5 mm was found: for buckwheat powder – 41.76%, for oatmeal – 52.56%.

Table 5.8 Sieve analysis results

Sieve size	$\bar{d}$, *mm*	Buckwheat powder, A (%)	Oat powder, A (%)
< 2.0	2.5	0.96	3.34
2.0–1.1	1.55	5.52	20.36
1.1–0.5	0.8	41.76	52.56
0.5–0.25	0.375	35.84	16.90
> 0.25	0.2	15.92	6.84

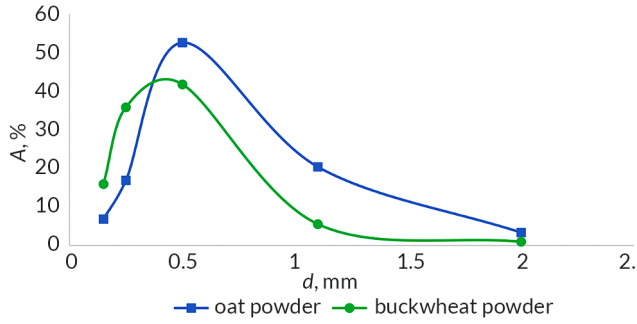

Fig. 5.2 Differential curves of buckwheat and oat powders particle size distribution

The analysis of the infrared spectra of oat and buckwheat powders (**Fig. 5.3**) shows that both samples have a similar chemical composition, typical of plant-based products. The main components are carbohydrates, proteins, fats, water and mineral compounds. However, there are significant differences in the intensity and location of individual bands, which allows to identify the specific characteristics of each sample.

Characteristic C-O valence bands in the range of 1000–1300 cm^{-1} (1238–1076 cm^{-1} in oatmeal and 1237–1077 cm^{-1} in buckwheat powder) are observed in both powders. This indicates the presence of polysaccharides (starch, fiber) as the main components. Low-frequency bands (500–800 cm^{-1}) indicate the structural features of these carbohydrates.

Amide bands in the range of 1500–1600 cm^{-1} (amide I and amide II) confirm the presence of proteins. In both samples, these bands are clearly defined, although in buckwheat powder they have a higher intensity, which may indicate a higher content of protein compounds. The C-H valence vibrations in the range of 2800–3000 cm^{-1} (2920–2852 cm^{-1} in oatmeal powder and 2929–2852 cm^{-1} in buckwheat powder) demonstrate the presence of methyl and methylene groups characteristic of fatty acids.

The broad O-H vibrational bands in the range of 3200–3600 cm^{-1} (3276 cm^{-1} in both powders) indicate residual moisture as well as alcohols that are part of carbohydrates. In buckwheat powder, there is a band of 1743.00 cm^{-1}, which indicates a significant presence of carbonyl compounds. These can be fatty acid esters, aldehydes or ketones, which are metabolic products. In oat powder, this area is less pronounced.

More intense amide bands (1587.85, 1562.26, 1530.76 cm^{-1}) were observed in buckwheat powder, indicating a higher protein content. This is consistent with the general composition of buckwheat, which is known for its high content of amino acids and proteins.

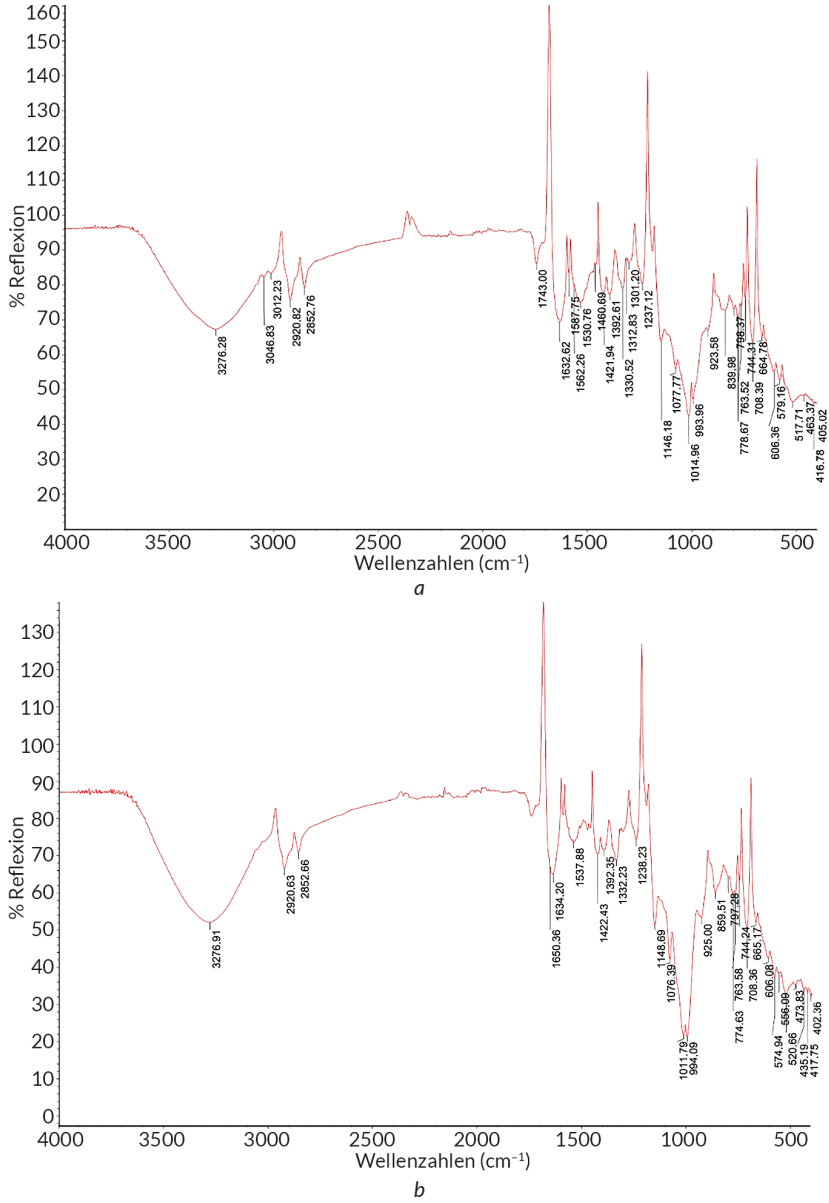

Fig. 5.3 Infrared absorption spectra of buckwheat (*a*) and oat (*b*) powders

A unique band of 839.98 cm^{-1} is present in buckwheat powder, which is not found in oat powder. This may be due to the peculiarities of the starch structure or aromatic compounds inherent in buckwheat. Additional bands in the region of 3000–3100 cm^{-1} (3046.83, 3012.23 cm^{-1}) were observed in buckwheat powder, which may indicate the presence of unsaturated fatty acids, while they are absent in oat powder.

Thus, oat powder is characterized by a high content of polysaccharides, as evidenced by strong C-O vibrations, and less pronounced carbonyl groups, indicating a low content of fats and simple sugars. This makes it a more neutral product with a high carbohydrate content. Buckwheat powder has a more pronounced protein profile (powerful amide bands), a significant content of fats and carbonyl compounds, which confirms its richer chemical composition.

The X-ray spectral analysis of the buckwheat and oat powders under study was carried out. **Table 5.9** shows the results of the quantitative determination of the relative content of elements in the studied samples: sample 1 – the average relative content of elements in buckwheat powder, sample 2 – the average relative content of elements in oat powder. The study was carried out in triplicate. The X-ray fluorescence analysis showed that both samples contain mainly C, H, P, S, K, Ca, Mn, Fe, Cu, Zn, but in different proportions. Buckwheat powder is characterized by a higher content of potassium and phosphorus, while oat powder has an increased level of calcium and manganese. The X-ray fluorescence spectra for the samples under study are shown in **Fig. 5.4**. The maximum peak in the spectra corresponds to an intensity of 35000.

Table 5.9 Results of quantification of the relative content of elements

Buckwheat powder, wt. %				
H	C	P	S	K
14.24037 ± 0.06	84.84687 ± 0.4	0.46452 ± 0.2	0.13848 ± 0.08	0.29713 ± 0.1
Ca	Mn	Fe	Cu	Zn
0.00863 ± 0.003	0.00086 ± 0.0003	0.00130 ± 0.0004	0.00031 ± 0.00009	0.00130 ± 0.001
Oat powder, wt. %				
H	C	P	S	K
14.31301 ± 0.03	85.27965 ± 0.2	0.10123 ± 0.05	0.05630 ± 0.01	0.22803 ± 0.2
Ca	Mn	Fe	Cu	Zn
0.04575 ± 0.02	0.00324 ± 0.002	0.00162 ± 0.0006	0.00015 ± 0.000004	0.00149 ± 0.0004

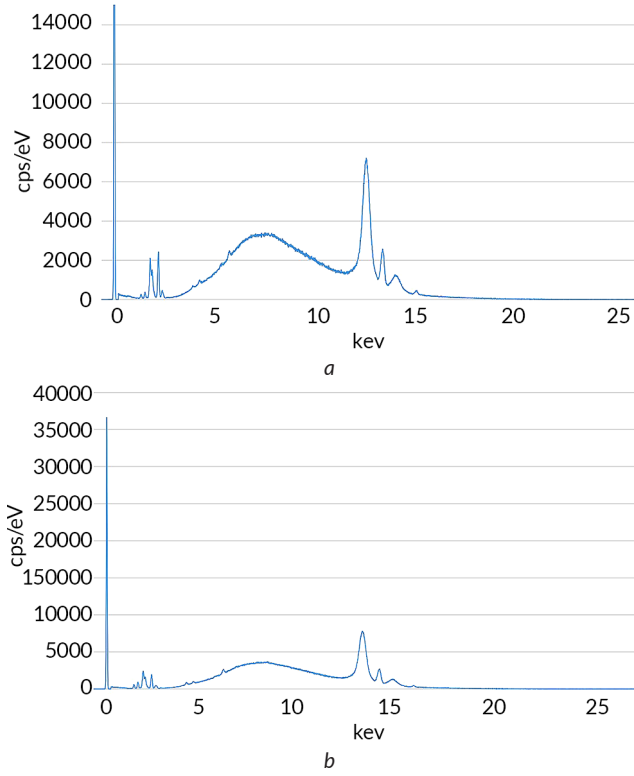

Fig. 5.4 X-ray fluorescence spectra of buckwheat (*a*) and oat (*b*) powders

In order to clarify the qualitative composition of buckwheat and oat powders, a study was carried out by gas chromatography with mass spectrometry (GC/MS). The obtained chromatograms are shown in **Fig. 5.5**. The peaks were processed and identified based on the comparison of chromatographic and mass spectral data with open source library data (NIST 2017 and Wiley 5th Edition).

In the studied samples of buckwheat and oat powders, 15 and 18 characteristic components were found, respectively, as shown in **Table 5.10**.

Buckwheat and oat powders contain similar groups of compounds, including Sucrose, Palmitic acid, 9,12-octadecadienoic acid (and its derivatives), Campesterol and Gamma-sitosterol. However, buckwheat powder is noted for its high content of antioxidants, such as Gamma-tocopherol (vitamin E), and macrocyclic lipids, which may indicate its strong antioxidant and bioactive properties. In contrast, oat powder

contains a wider range of sterols (Stigmasterol, Fucosterol), oxazole derivatives and steroidal compounds, including 11(α),17(α)-dihydroxyprogesterone, which may contribute to its metabolic and hormonal benefits. In addition, Linoleyl palmitate was found in oat powder, which indicates a higher content of complex lipids that may increase its nutritional value.

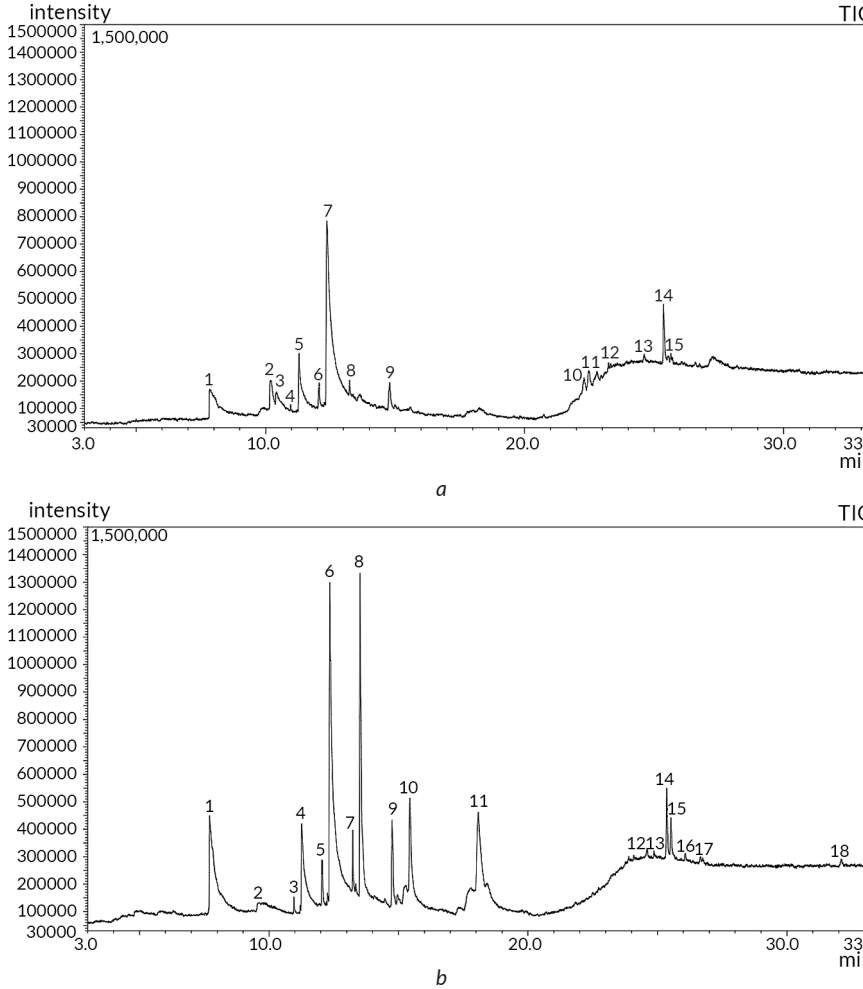

Fig. 5.5 Chromatograms of buckwheat (*a*) and oat (*b*) powder extracts

Table 5.10 Results of the chromatography-mass spectrometry study

Peak	R. Time	I. Time	F. Time	Area	Height	Name
1	2	3	4	5	6	7
Buckwheat powder						
1	7.841	7.810	7.913	292347	77324	Sucrose
2	10.193	10.130	10.280	628117	100663	Hexanamide
3	10.423	10.377	10.440	117553	37192	13-Docosenamide, (Z)-
4	10.965	10.937	11.000	32388	22951	Methyl Palmitate
5	11.288	11.253	11.473	1138304	206451	Palmitic Acid
6	12.040	12.010	12.050	77571	65284	9,12-Octadecadienoic acid (Z, Z)-, methyl ester
7	12.363	12.317	12.753	7339446	664846	9,12-Octadecadienoic acid (Z, Z)-
8	13.240	13.207	13.297	110185	56059	Octadecanoic acid, 2-(dimethylamino)ethyl ester
9	14.783	14.710	14.883	456477	96959	2-(Dimethylamino)ethyl vaccenoate
10	22.292	22.203	22.340	248211	52280	Tricyclo[20.8.0.0(7,16)]triacontane, 1(22),7(16)-diepoxy-
11	22.475	22.390	22.547	333855	62795	Trilinolein
12	23.238	23.200	23.267	49458	26526	Gamma-Tocopherol
13	24.618	24.563	24.653	70201	23900	Campesterol
14	25.367	25.313	25.487	769366	215153	Gamma-Sitosterol
15	25.648	25.603	25.680	101920	38063	Germanicol
Oat powder						
1	7.710	7.630	8.123	3648291	347997	Sucrose
2	9.577	9.503	9.690	236986	28314	3-Deoxy-d-mannoic lactone
3	10.965	10.903	11.030	110556	59107	Methyl Palmitate
4	11.264	11.183	11.737	3234057	322832	Palmitic Acid
5	12.040	12.010	12.190	542558	160288	9,12-Octadecadienoic acid, methyl ester
6	12.350	12.310	12.937	10269548	1161975	9,12-Octadecadienoic acid (Z, Z)-
7	13.240	13.183	13.330	425544	212373	Octadecanoic acid, 2-(dimethylamino)ethyl ester
8	13.518	13.457	13.910	4921115	1174524	2-((8Z,11Z)-Heptadeca-8,11-di-en-1-yl)-4,5-dihydrooxazole

Continuation of Table 5.10

1	2	3	4	5	6	7
9	14.753	14.683	14.903	1299566	312563	2-(Dimethylamino)ethyl vaccenoate
10	15.441	15.343	15.777	2494207	378531	Hexadecanoic acid, 2-hydroxy-1-(hydroxymethyl)ethyl ester
11	18.087	17.943	18.330	3082328	291700	9,12-Octadecadienoic acid (Z, Z)-, 2-hydroxy-1-(hydroxymethyl)ethyl ester
12	24.598	24.523	24.670	108019	31778	Campesterol
13	24.868	24.830	24.897	35842	19445	Stigmasterol
14	25.362	25.283	25.477	853751	256939	Gamma-Sitosterol
15	25.525	25.477	25.683	560112	148904	Fucosterol
16	26.080	26.037	26.150	93279	27221	Stigmasta-7,24(28)-dien-3-ol, (3.beta, 5.alpha)-
17	26.745	26.697	26.783	72169	20750	11(alpha),17(alpha)-Dihydroxy-progesterone
18	32.108	32.030	32.203	99768	22052	Linoleyl palmitate

Analysis of the chemical composition of buckwheat and oatmeal powders by chromatography-mass spectrometry revealed the presence of common and unique bioactive compounds. Buckwheat powder is a promising source of antioxidants, while oat powder contains a significant amount of bioactive lipids and sterols that may have a regulatory effect on lipid metabolism. The results obtained can be used for further research on the use of these products in functional food and pharmacology.

5.5 Conclusions

Buckwheat and oats are important components of functional foods due to their unique chemical composition and beneficial properties. This conclusion was confirmed by a comprehensive analysis of buckwheat and oat powders, including sieve analysis, infrared spectroscopy (IR spectroscopy), X-ray fluorescence analysis (XRF) and gas chromatography with mass spectrometry (GC/MS). Buckwheat contains high quality vegetable protein (compared to oatmeal powder, more intense amide bands of IR spectra at 1587.85, 1562.26, 1530.76 cm^{-1}) with an optimal amino acid

balance, which promotes tissue growth and repair. It is rich in flavonoids, which strengthen blood vessels and reduce the risk of cardiovascular disease. Buckwheat also contains iron (0.00130%), calcium (0.00863%) and zinc (0.00130%), which improve blood formation and support the nervous system. Buckwheat's dietary fiber helps to normalize digestion and reduce cholesterol levels.

Oats are a source of beta-glucans, a soluble dietary fiber that reduces blood glucose and cholesterol levels. Oat groats contain a significant amount of avenanthramides, polyphenols (stigmasterol, fucosterol, 11(α),17(α)-dihydroxyprogesterone) with antioxidant and anti-inflammatory activity. Thanks to its low glycaemic index, oats help stabilize blood sugar levels, making them beneficial for people with diabetes. Magnesium and B vitamins in oats have a positive effect on the functioning of the nervous system and energy metabolism. Oats are also a source of potassium (0.22803%), calcium (0.04575%) and iron (0.00162%), and are high in manganese (0.00324%), which is important for bone health. Regular consumption of buckwheat and oats as part of a functional diet helps to promote health, improve metabolism and prevent chronic diseases.

Oatmeal powder may be preferred for the manufacture of dietary products rich in fiber and carbohydrates, but with a reduced fat content. Buckwheat powder is suitable for products with a high nutritional value, focused on enhanced protein and fatty acid composition. Grinding buckwheat and oat groats improves their digestibility and reduces cooking time. This also allows them to be used in the production of flour, instant cereals and baby food. In addition, crushed cereals give dishes a softer texture and better uniformity. The synergy of buckwheat/oat mixtures and the impact of cereal processing will be the subject of further experimental research.

The comparative analysis of the biochemical characteristics of buckwheat and oat cereals in this article aims to expand the scientific understanding of their potential as functional foods, to assess their potential impact on human health and to determine the possibilities of their integration into a balanced diet. In addition, such an analysis contributes to the diversification of agricultural production by offering an alternative to monoculture farming. The authors hope that the analysis presented in this article will be useful for food producers, nutritionists and consumers, highlighting the benefits of including these crops in the daily diet.

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CHAPTER 6

Justification and development of biotechnology of cooked sausage products for health purposes

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Abstract

Today, meat products are the most important component of the population's diet, as their share in the total volume of consumption amounts to a quarter, with the largest portion attributed to sausage products. However, the consumption of sausage products can have negative health consequences, since such finished products contain from 2 to 6% of table salt, as well as sodium nitrite. Given this, our main task was to reduce the amount of sodium entering the human body and reduce the amount of sodium nitrite used.

According to the research results, a recipe for "Ozdorovchi" sausages was developed using blood plasma protein in the amount of 1.0%, citrus dietary fiber in the amount of 0.5%, rosemary extract in the amount of 15 g/100 kg of the main raw material. The cumulative effect of the action of raw materials of plant and mineral origin in reducing the addition of sodium nitrite in the production of new types of sausages was established. The possibility of using the above food ingredients was proven, which made it possible to increase the functional and technological properties and biological value of new types of health-improving sausages.

Keywords

Sausage products, rosemary extract, bacterial preparation, sea salt with laminaria, biological value.

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6.1 Introduction

Nutrition is one of the most important factors in normalizing health [1]. One of the important conditions that is set when organizing a well-balanced and, specifically, health-conscious diet is the absence in the diet of substances that can have a negative impact on the health of the consumer [2].

Currently, the prevailing trend in the modern food industry is to improve traditional and develop innovative technologies and meat products in order to obtain finished products characterized by a high level of quality, environmental friendliness, and biological safety [3–5].

One of the largest components of the modern consumer's diet is meat products. According to the World Health Organization (WHO), the share of such food products in the total consumption accounts for more than 1/4, and among them, the largest share is sausage products [6].

However, consumption of food products derived from meat can lead to negative consequences for human health. For instance, sausage mince contains 2...6% of table salt, potentially dangerous for human health sodium nitrite, and, usually, finished products derived from meat using traditional technology are not always characterized by increased nutritional value [7].

One of the promising ways to avoid these negative impacts is the partial or complete replacement of traditionally used additives and ingredients with non-traditional types and their additional inclusion in the recipe compositions of meat products, in particular, to intensify the technological process [8].

Therefore, improving the technology of meat products with research and scientific justification for the use of promising raw materials, additives, and ingredients of animal, mineral, and plant origin is of important scientific and practical importance and is an urgent task.

6.2 Justification of the use of ingredients and additives to improve sausage technology

The task was to develop an improved technology for minced meat mixtures, characterized by an increased level of safety for the health of potential consumers and improved physicochemical and organoleptic properties. The product proposed for implementation is intended to be used in the production of health-improving sausages.

The objects on which the research was conducted were sausage minced meat modified with functional additives determined according to the research

results (hereinafter coded as "Experiment 1") and sausages after the full technological production cycle, for the manufacture of which this minced meat was used (coded as "Experiment 2"). The object of comparison was selected as sausages according to DSTU 4436:2005 "Cooked (boiled) sausages, Sausages, Small Sausages, Meat Loaves. General technical requirements" is given in the **Table 6.1**.

Table 6.1 Formulation of "Liubytelski" sausages

Name of raw materials, spices and materials	Norm
Unsalted raw materials, kg/100 kg	
Beef, trimmed, first category	35
Lean pork, trimmed	40
Back fat	25
Spices and materials, g/100 kg of unsalted raw material	
Table salt	2500
Sodium nitrite	5.6
Granulated sugar or glucose	110
Ground black or white pepper	85
Ground nutmeg or cardamom	55

Source: [9]

Determination of the influence of table sea salt on the functional properties of meat raw materials. Functional (technological) properties of meat raw materials in the sausage production process are understood as a complex of physicochemical indicators of the influence on the structure and consumer properties of minced meat systems obtained from it. In their formation, an important role belongs to muscle tissue proteins, which, not taking into account the water inherent in meat systems (56...72%), are their main component – 15...22% and one of the main properties of interest to technologists is the ability of minced meat to retain and bind and retain moisture by mass (otherwise – water-holding capacity (WHC)) [10].

In part, polar water molecules contained in muscle tissue are tightly held by the characteristic localized charge polar groups of protein molecules due to hydrogen bonding and do not migrate outward from this close vicinity [11].

Ground muscle tissue can hold 700 to 800 grams of moisture per 100 grams of protein, but after slaughter, the muscle's ability to hold moisture decreases, mainly due to an increase in the number of lactic acid bacteria in the meat mass and the lactic acid they generate [12].

The inevitable loss of part of the bound moisture mass by meat affects its organoleptic properties, primarily tenderness and juiciness, which are of primary importance to consumers of meat products. It follows that the primary task set in this work was to develop a method for improving the taste and tactile characteristics of meat products aimed at finding ways to retain a sufficient amount of water in the meat system.

The first discovered way to achieve the task was to use the method of periodic mixing of the minced meat system with the neutralization of part of the lactic acid formed in it, which is the optimal condition for accelerating meat aging. This also allows to reduce the time of loss of moisture by meat in the process of postmortem stiffening, accompanied by the loss of the ability of the mass to retain calcium in the intercellular space and the destruction of hydrogen bonds existing during life between water and polar groups of actin and myosin of muscle tissue [11].

However, in the process of muscle tissue aging, the phenomenon of hardening disappears, and its resolution is accelerated under the action of microorganisms' strains introduced with starter cultures. As a result, muscle tissue cells acquire the ability to take a certain part of the water from the intercellular space of meat, for which the osmotic pressure of free moisture should be reduced in them. Usually, the problem of increasing the level of WHC is solved by salting meat raw materials. As a result of the diffusion of salt introduced with brine, the osmotic pressure of water in the cells decreases and becomes less than in the intercellular space. The result is the diffusion of part of the free water from it into the cells, accompanied by improved tenderness and increased juiciness of the meat component [11].

This technique, which is also an integral part of the technological process of sausage production, has become the subject of research, since correctly selected parameters and durations of salting allow obtaining a finished product of the best quality with the least costs. The first, determining criterion when choosing a salt grade for salting was to determine the probable differences in the sensation of saltiness of samples prepared with ordinary table salt and with sea salt enriched with laminaria according to TU U 14.4-34161267-001:2007. The reason, as noted, is that the only salt that actually has a salty taste is sodium chloride, and its content in sea salt is approximately 30% lower than in commercial table salt. Their respective compositions are given in **Table 6.2**.

The degree of saltiness of real minced meat prepared with these salts was not determined for a number of reasons, but the degree of saltiness of their aqueous solutions was investigated in the concentration range of 0.5...2.5% by sensory evaluation method with subsequent scoring. This range was chosen for the reasons that the mass fraction of salt in the most concentrated solution approximately corresponded to the corresponding indicator of the mass fraction of NaCl, traditionally used in

sausage products. The assessment of the level of saltiness in points was carried out using the organoleptic method. The results of the assessment are shown in **Fig. 6.1**.

Table 6.2 Standardized composition of table salt and laminaria-enriched sea salt

Indicator	Norm in terms of dry matter	
	Premium quality table salt	Sea salt with laminaria
Sodium	38.4	30.6
Chloride	59.3	55.0
Calcium	0.4	1.2
Potassium	0.1	1.1
Magnesium	0.005	3.7
Iron	0.8	n. i.
Sulfate	–	7.7
Hydrocarbonate	0.85	0.41
Iodine	–	5×10^{-6}
Insoluble residue	0.25	0.03
Humidity	3.20	0.10

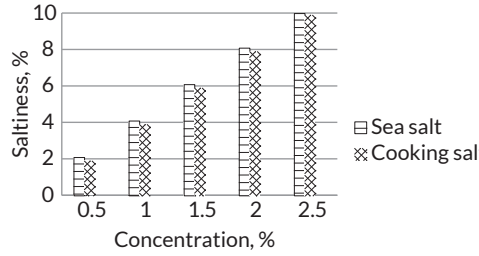

Fig. 6.1 Results of organoleptic evaluation of the solutions saltiness degree

The obtained data show that the solutions saltiness, despite the significantly different ionic composition of the dissolved salts, practically does not differ in the entire studied range. On this basis, it was concluded that when salting, it is advisable to use not rock salt, but sea salt and thus achieve a significant reduction in the potential adverse effects of salt on the human body [13].

In addition, sea salt contains more than 40 trace elements, the most significant of which (in comparison with the corresponding quality indices of ordinary salt) should be recognized as the following (**Table 6.3**).

Table 6.3 Trace element content in table salt and laminaria-enriched sea salt

Element name	Element concentrations in salt samples, μg/g	
	Table salt	Sea salt with laminaria
Sulfur	46349.74 ± 3807.10	76442.78 ± 4992.50
Manganese	–	1.62 ± 0.89
Chrome	–	3.97 ± 1.33
Cobalt	–	2.44 ± 1.09
Copper	3.81 ± 1.76	2.40 ± 0.94
Selenium	5.98 ± 2.07	1.43 ± 0.47
Zinc	144.76 ± 7.04	3.56 ± 1.09
Bromine	6.40 ± 1.26	319.80 ± 7.37
Rubidium	83.05 ± 3.21	10.38 ± 1.12
Strontium	–	13.28 ± 1.29
Zirconium	–	1.76 ± 0.44
Iodine	62.2 ± 15.68	3.86 ± 1.46

The aim of the study was to determine the change in organoleptic properties of minced meat when switching from regular rock salt to sea salt. The objects of the study were beef and pork, which were salted in comparison with sea salt in parallel with regular table salt. Salting was carried out according to the technology generally accepted in the meat industry: salt was added to the minced meat mixture at the rate of 2.4 grams per 100 grams of minced meat, and the mixture was kept at 4°C and periodically stirred for 24 hours. The obtained indicators of the ability of meat to bind moisture after salting are shown in **Fig. 6.2** and **Fig. 6.3**.

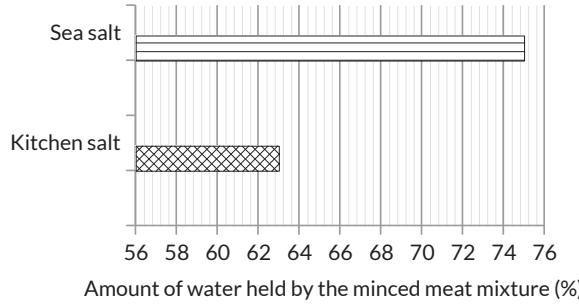

Fig. 6.2 Amount of water retained by beef during salting, %

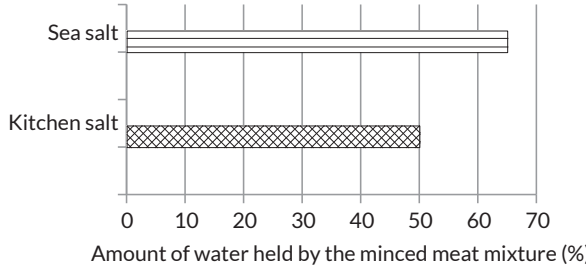

Fig. 6.3 Amount of water retained by pork during salting, %

The data obtained indicate that the use of sea salt during salting allows to increase the moisture binding capacity of both beef and pork, the reason for which is probably the presence in the system of a sufficient number of potassium, magnesium and potassium ions, which are characterized by an increased hydration number, and are absent in significant quantities in table salt [11].

An additional argument in favor of this conclusion is the enrichment of the minced meat mixture with acutely deficient iodine and a number of beneficial trace elements. Since iodine is not synthesized in the body, the only way to obtain it is to consume iodine-rich foods: fish, eggs, nuts, meat, bread, dairy products, algae, and iodized table salt. In the absence of the possibility of consuming a sufficient amount of these products in food, according to the recommendations of the World Health Organization, it is advisable to add iodine compounds to sodium chloride used for food purposes [14]. On this basis, let's conclude that replacing the rock table salt usually used for salting meat raw materials with sea salt is advisable.

The next step of the research was to find a way to enrich the salt used for salting meat raw materials with mineral salts that are vital for the normal state of the body, primarily potassium compounds and iodine, which is acutely deficient in most regions of Ukraine. The task facing us when choosing the type of salt recommended for use in salting was to find the optimum, under which the necessary conditions for the aging of meat raw materials would be ensured while providing the human body with a sufficient amount of minerals necessary for its normal functioning, primarily potassium, the need for which for an adult reaches 3500 milligrams per day [15].

Elementary calculations show that parity in sodium and potassium intake would be achieved if the ratio of their chlorides in the mixture recommended for consumption was about 50:50 by weight. However, despite the fact that most everyday products contain a fairly large amount of potassium, the content of which in some of them is the amount of potassium added with salting salt, may be less. Therefore, like most

foreign developers, it is possible to believe that when salting meat raw materials, it would be more rational to use salts that would contain 30% potassium chloride and 70% sodium chloride.

In Ukraine, according to the requirements of the national standard DSTU 4307:2004, iodized salt with a mass fraction of iodine in $(40 \pm 15) \times 10^{-4}$%, or 40 ± 15 milligrams of iodine, is produced with the addition of potassium iodate (KJO_3) and, to counteract caking, a microadditive of toxic potassium ferrocyanide. The level of its use in cooking allows, to some extent, to reduce iodine deficiency in the diet [16].

However, with the recommended weekly intake of approximately 100 micrograms of iodine for a 70-kilogram person consuming only iodized salt and the actual daily intake of approximately 10 grams of salt, the body will consume 400 ± 150 micrograms of iodine during this period, which may cause health problems, primarily due to the negative impact on the retina. The negative impact of inorganically bound iodine can be partially mitigated by using sea salt, which contains significant amounts of organically bound iodine, as well as its commercially available varieties enriched with seaweed [11].

The choice of a specific type of algae recommended for addition to the salt used for salting meat raw materials was made by us taking into account their commercial availability and actual iodine content. Analysis of world experience and availability of iodine-rich algae resources showed that the optimal choice is laminaria, and the method of enriching salt with this trace element is the introduction of its finely ground leaves or extract into the system. Organically bound iodine introduced into the system, in contrast to iodine added with potassium iodate, is stored in the mass for a long time and is not destroyed by light and during food preparation. The advantage of this form of its presence is almost complete digestibility, moreover, in the quantities necessary for normal life, since excess iodine is excreted from the body without any toxic effects [11].

The product also contains vitamins A, B_1, B_2, B_{12}, C and D and a whole range of micro- and macroelements important for the body (**Table 6.4**).

Taking into account this factor and the analysis of the salt market in Ukraine, the requirements are fully met by the first-grade sea salt TU U 14.4-34161267-001:2007, which consists of 70% sodium chloride, 30% potassium chloride and contains an additive of ultra-crushed dry laminaria leaves (seaweed). The salt, in preference to rock salt, also contains a number of valuable trace elements (**Table 6.5**).

The use of this salt, characterized by a reduced sodium content and enriched with potassium and valuable trace elements, can be recommended for widespread use, especially for the following population groups [17]:

– people with high blood pressure;

– with obesity and edema;

– for people who control their blood sugar levels;
– people with increased emotional and physical stress.

Table 6.4 Trace element content in dry laminaria leaves (mg/100 g)

Element	Contents
Magnesium	1.26
Silicon	0.51
Phosphorus	0.41
Iodine	0.25
Calcium	0.22
Iron	0.12
Zinc	0.002
Vanadium	0.0016
Manganese	0.001
Nickel	up to 0.00017
Cobalt	< 0.00016
Molybdenum	0.000096

Table 6.5 Trace element content in sea and table salt, μg/kg

Element	Salt grade	
	Sea	Table
Chrome	3.97 ± 1.33	–
Iodine	3.86 ± 1.46	–
Zinc	3.56 ± 1.09	5.98 ± 2.07
Cobalt	2.44 ± 1.09	–
Copper	2.40 ± 0.94	3.81 ± 1.76
Manganese	1.62 ± 0.89	–
Selenium	1.43 ± 0.47	–

Justification and research of the use of dietary fibers in meat products. One of the ways to eliminate the deficiency of dietary fiber consumption is their introduction into food compositions. Currently, there is a large number of fibers of plant origin on the market and the criteria that should be taken into account when choosing a specific type of fiber are their chemical composition, respectively, and the physiological orientation of the main components [18].

When developing the recipe for minced meat for health-improving sausages, let's conduct studies to determine the ability of fibers available in mass production of the product to retain moisture in the composition. For comparison, the same test method was applied to ready-to-eat fiber-modified meatballs made according to the same recipe (200 grams of ground beef + 2 grams of salt + 1% of the corresponding fiber). The data obtained during the experiment are shown in **Fig. 6.4**.

According to this data, the greatest amount of moisture is retained by orange dietary fiber, the specific composition of which is given in **Table 6.6**.

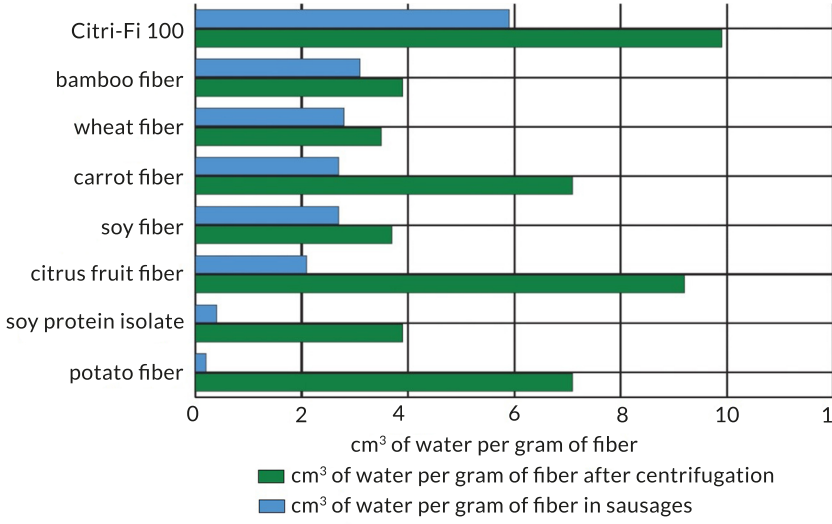

Fig. 6.4 The ability of dietary fibers of plant origin to retain moisture

Table 6.6 Chemical composition of orange fibers Citri-Fi 100, %

Indicator	Parameter value
Mass fraction of moisture	9.25 ± 0.10
Mass fraction of insoluble dietary fiber	53.07 ± 1.23
Mass fraction of soluble dietary fiber	17.97 ± 1.40
Mass fraction of proteins	0.43 ± 0.08
Mass fraction of fat	6.57 ± 0.52
Mass fraction of ash substances	3.43 ± 0.04
Mass fraction of the sum of phenols	4.89 ± 0.02

The positive properties of orange dietary fibers include the fact that they contain a large number of flavonoid components with antioxidant activity and, to a certain extent, bactericidal properties (2.2-azino-bis-3-ethylbenzothiazoline-6-sulfonic acid, 2.2-diphenyl-1-picryldrazyl, 2.2-azobis-2-methyl-propanilamide, etc.). For these reasons, minced meat modified with the addition of orange fibers is characterized by an extended shelf life and does not require additional addition of synthetic antioxidants, many of which have a negative effect on the condition of the gastrointestinal tract. The significant advantages of Citri-Fi fibers include their ability to sorb and remove slags and heavy metals with the insoluble fiber fraction, i.e., providing products containing them with certain therapeutic and prophylactic properties, including practically stopping the formation of inflammatory mediators, primarily nitrogen monoxide [19].

The introduction of orange dietary fibers into meat compositions makes it possible, in addition to providing the body with functions of improving digestion and removing toxins from the body, to use fattier raw materials in production and, at the same time, reduce the fat taste in the composition, optimize the stages of dosing and packaging of the finished product, improve its structure, reduce calorie content, and reduce the risk of brine inclusions in the mass [19].

Due to the high content of bioactive substances, orange fibers are recommended for use in the food industry, in particular the meat industry, to increase juiciness and improve the structure of sausages, salami and low-fat products. The main advantages of their use should be recognized as [19]:

– prevention of cancer due to the presence of flavonoids and limonene;

– preventing the accumulation of mucus in the lungs and preventing the development of lung diseases due to the presence of vitamin C;

– alleviation of the effects of diabetic complications due to the presence of pectin, which helps normalize the amount of glucose in the blood;

– promoting health due to the presence of the flavonoid hesperidin, which helps lower blood pressure and eliminate cholesterol;

– promoting weight loss by reducing the amount of fiber-rich foods consumed;

– preventing eye inflammation and increasing visual acuity due to the presence of limonene and citral;

– reducing the likelihood of developing caries.

The complex of such properties was the reason why it is possible to choose the orange fibers Citri-Fi 100, which are widely available on the market when developing the recipe for sausage minced meat.

Justification of the feasibility of using blood plasma proteins in minced meat compositions. Modern trends in increasing the nutritional and biological value of meat products from the point of view of protein consumption, taking into account

the reduction of meat resources, are implemented in the development and increasingly widespread use of sausage production technologies, where some of the meat components, in particular fat, are replaced by alternative raw material sources and one of the main requirements for products of modified composition is their improved consistency and organoleptic quality indicators and a sufficient amount of food protein as a source of building body cells. However, at the same time, according to the principles of nutrition, the human body needs not just food protein but protein characterized by a complete amino acid composition, which is what animal proteins are best suited for. Among the ingredients recommended for widespread use in meat systems, proteins obtained by processing blood occupy a prominent place. They contain albumins, globulins, a significant amount of essential amino acids, and some other components [20].

Characteristics and justification for the use of rosemary extract. Meat systems are a set of a large number of components, most of which are unstable and undergo changes when exposed to air. In many cases, during the attack on them by oxygen, unstable peroxides and free radicals are formed in the system – highly chemically active groups of atoms characterized by the presence of an unpaired electron. These newly formed compounds are characterized by an adverse effect on cell membranes, resulting in the cells losing their inherent protective properties and a person ages prematurely. Such processes are characteristic, however, not only for living organisms but also for meat obtained after slaughtering an animal, especially that which is characterized by a high fat content [11].

The problem of ensuring high-quality storage of the product on the one hand and the stability of organoleptic and physicochemical properties on the other, in the case of meat systems, becomes particularly critical since their main component meat is characterized by a large number of compounds capable of oxidation, primarily lipids, and rancidity and general spoilage of products. Therefore, one of the main tasks in the meat industry is to solve the issue of safe inhibition of oxidative processes in meat products. To minimize the speed of these processes, the food industry uses a number of methods, including control of climatic conditions for storing finished products, careful selection of packaging methods and packaging materials, etc. Usually, this problem is solved by introducing substances with antioxidant properties into the composition. Among those used to extend the guaranteed shelf life of meat products, plants and plant extracts are widely used, which, as products of their metabolism, contain the so-called characteristic antibacterial flavonoids (natural phenolic compounds that accumulate in all plant organs in the form of glycosides) [21].

Despite the fact that rosemary has practically no nutritional value (15.1 kJ/kg), its introduction into minced meat compositions can also be recommended in view

of giving them a "spicy" flavor since the plant contains from 0.5% to 2.5% of volatile aromatic compounds, mainly terpenes [11].

Introduction into the minced meat mixture of an additive characterized by an active antioxidant effect (i.e., the property of priority interaction with oxidants) of rosemary extract, which, in addition to giving the finished product pleasant aromatic properties, almost entirely – 0.912 grams in one gram – consists of compounds characterized by the ability to primarily interact with oxidants and thereby protect other compounds present in the system from oxidation by newly formed in the minced meat mass and characteristic active oxidative properties of tetravalent and pentavalent nitrogen compounds (respectively, NO_2 and HNO_3) [11].

In this variant, the nitrite ion added to give the meat mass an attractive pink-red color is almost quantitatively spent on the target reaction of nitrosomyoglobin formation, which allowed to significantly reduce the dosage of toxic nitrite when realizing the desired color of sausage products while its practical absence in the finished sausage products [11].

In order to determine the optimal dosage of rosemary extract from the point of view of extending the guaranteed shelf life, its additive was introduced into the sausage stuffing and the dynamics of changes in the peroxide value of the sample during storage were determined. The indicator characterizes the instability over time of the meat system due to the interaction of its components with atmospheric oxygen, accompanied by the formation of peroxides (compounds of a peroxide nature) and other substances with characteristic oxidizing properties. The higher the peroxide value of the antioxidant-modified substance, the lower its stability over time and the shorter the guaranteed shelf life. The presence of peroxides is detected due to their ability to interact with potassium iodide with the release of molecular iodine. The quantitative content of the formed peroxides is further determined by titration of the released iodine with sodium thiosulfate [11]

$$2Na_2S_2O_3 + J_2 \rightarrow 2NaJ + Na_2S_4O_6.$$

The mechanism of the protective action of the additive is that nitrogen dioxide NO_2, characterized by high oxidative activity, formed during the rapid decomposition of unstable nitric acid in the biological environment, almost instantly interacts with the antioxidant components of rosemary extract with repeated conversion into nitrogen monoxide NO and the process of oxidation-reduction of nitrogen occurs in accordance with its acquisition of oxidation states II (NO) $\rightarrow$ IV (NO_2) $\rightarrow$ II (NO), that is, "in a circle". The positive effect of using rosemary extract occurs according to this method due to the fact that nitrogen monoxide NO, formed either during the initial

decomposition of sodium nitrite after its introduction into minced meat in the form of salt or due to the interaction of the newly formed nitrate ion with antioxidants introduced with rosemary, is spent on the formation of the target compound nitrosomyoglobin almost entirely. This is the difference of the claimed method, according to which a reduced dosage of sodium nitrite is used in the preparation of the product, part of which, according to traditional technology, is spent on the synthesis of the ballast additive sodium nitrate [11].

According to the results of the experiment, it was determined that the peroxide value monotonically increases in all the samples studied, but in the presence of rosemary, the rate of its increase was significantly lower than in the control sample with the simultaneous refusal to add synthetic antioxidants to the mass, and the optimal dosage should be considered to be 0.15% of the extract in relation to the meat raw material since its further addition practically does not affect the rate of growth of the controlled parameter [11].

Another criterion for improving the quality of minced meat by modifying it with the addition of rosemary extract is the dynamics of the change in the acid number of minced meat over time as a criterion for the rate of hydrolytic oxidation of lipids with the formation of fatty acids. The purpose of the determination was to establish an additional criterion for the feasibility of using rosemary extract in extending the shelf life of meat products at what we estimated as the optimal dosage of rosemary extract (0.15%) [11].

Given the implementation of undesirable transformations in the system of the traditional composition, the second task of developing a solution characterized by patent novelty was to find a way to avoid undesirable interactions. The task was proposed to be solved by introducing into the minced meat mixture an additive of rosemary extract, characterized by an active antioxidant effect (i.e., the property of priority interaction with oxidants), which, in addition to providing the finished product with pleasant aromatic properties, consists almost entirely – 0.912 grams in one gram – of the characteristic ability to primarily interact with oxidants and thereby protect other compounds present in the system from oxidation by newly formed in the minced meat mass and characteristic active oxidizing properties of tetravalent and pentavalent nitrogen compounds (respectively, NO_2 and HNO_3) [11].

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To determine the effectiveness of the antioxidant effect of the rosemary extract supplement, the preparation was added to the test samples of minced meat in an amount of 0.15% by weight. A sample of minced meat without the addition of the extract was used as a control. The samples were kept at +8°C for 10 days, and their acid number was periodically determined. The results of the determinations are shown graphically in **Fig. 6.5**.

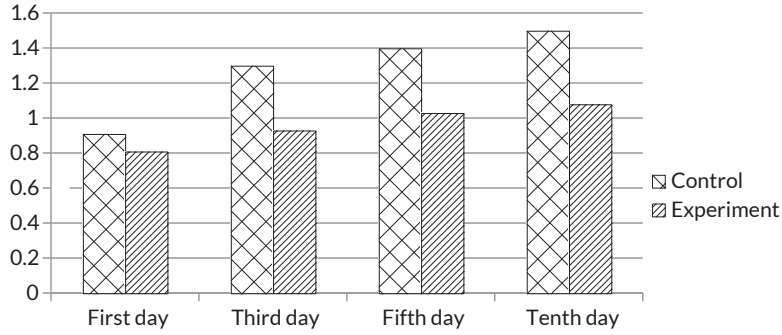


Fig. 6.5 Dynamics of changes in the acid number of control and experimental samples of sausage minced meat during storage

Studies confirm the high antioxidant activity of rosemary extract and its ability to inhibit the process of lipid oxidation in sausages effectively. The addition of the extract in an amount of 0.05–0.15% allows to slow down the hydrolytic oxidation of minced meat lipids by 29.75–40%, and the extract itself, depending on the technology used, can be added directly to the product in the form of a powder or a solution in water [13].

Justification of the feasibility of using the bacterial preparation "Iprovit LRR". Certain methods of modifying its composition and the sequence of technological operations are usually used to extend the guaranteed shelf life of the product. This approach was used by us in studying the dynamics of changes in the qualitative and quantitative composition of microflora and determining rational production parameters. The object of the study was the operation of salting meat raw materials. The duration of the process is quite high (up to 24 hours) at a temperature of 0...4°C and a relatively low concentration of sodium chloride in the mass. Such conditions are quite favorable for rapid development with sufficiently high bacterial contamination of meat raw materials [11].

Our studies showed that the beef and pork used to prepare the control and experimental samples contained a sufficiently large number of dangerous microorganisms: colonies of Escherichia coli (*E. coli*) were detected in samples weighing 0.0001 grams (with a detection rate of 0.01 grams), and mesophilic aerobic and facultative aerobic microorganisms (MAFAM) in the same sample were found in an amount of 2.9×10^5 colony-forming units (CFU) at the established rate ($1 \div 2 \times 10^3$) [11].

The commonly used method of further reducing their number by heat treatment at the stage of cooking sausage products allows to significantly reduce the level of bacterial contamination of the product at the time of manufacture, however, the meat composition is not protected from the reproduction of microorganisms in the future, as shown by the product analyses conducted over two days, when the number of MAFAM group bacteria formed is equal to colonies with the norm of absence within the limits of the used methodology (1×10^3). According to the results of the experiment, minced meat standardized by the DSTU 4436 standard contained 3.1×10^5 in one gram of MAFAM sample and showed the presence of Escherichia coli bacteria in the product in samples weighing 0.001 grams (the permissible level is the detection of presence in samples weighing 0.01 grams) [11].

Thus, it was faced with the task of solving two problems simultaneously: to reduce the level of bacteriological contamination of minced meat and maintain its acceptable level after the completion of the process of producing a sausage product from it, as well as to reduce the dosage level of the toxic impurity sodium nitrite in minced sausage [11].

The procedure for directed influence was the addition of the bacterial preparation "Iprovit LRR" recommended by the Institute of Food Resources to the minced meat, which includes bacteria of the *L. rhamnosus* strain and micrococci *Kocuria rosea*. The dosage of the preparation, according to the recommendations of the Institute of Food Resources of Ukraine, was 50 milligrams of dry preparation per kilogram of meat raw materials. The use of the preparation allows for the significant

improvement of the microbiological safety of the processed sausage minced meat due to the rapid development of beneficial microflora in the system (**Table 6.7**).

Table 6.7 Main parameters of microorganisms' growth in the preparation "Iprovit LRR"

Cultivation conditions	Components TC	$X \cdot 10^9$, CFU/cm^3	$v_{max.}$, hour^{-1}	v, hour^{-1}	T_l, hour	g, hour
Stationary conditions, with periodic neutralization	LAB	(4.0 ± 0.3)	0.85	0.59	2.33	1.18
	MC	(0.1 ± 0.1)	0.40	0.24	4.13	2.5
Without mixing, with periodic neutralization	LAB	(6.8 ± 0.1)	1.03	0.64	2.19	0.97
	MC	(0.2 ± 0.1)	0.44	0.27	2.82	2.27
	MC	(0.06 ± 0.2)	0.42	0.29	1.40	2.38
With stirring and with periodic neutralization	LAB	(3.0 ± 0.2)	0.95	0.56	0	1.05
	MC	(0.08 ± 0.2)	0.44	0.30	1.19	2.27

The mechanism of the positive effect of the preparation can be summarized as follows:

1) acceleration of the increase in the acidity level of the mass due to the faster growth of lactic acid bacteria of the Lactobacillus rhamnosus strain in it;

2) intensification of the denitrification process under the action of microorganisms of the Kocuria rosea strain of residual amounts of nitrite added to the minced meat and sodium nitrate formed from it.

An additional effect of using the preparation is the dominance of the reproduction of beneficial bacteria and the formation of substances (bacteriocins, antibiotics, peroxides, etc.) by the introduced strains of microorganisms during the metabolism process, which while preserving the biological value of enriched meat products, counteract the reproduction of undesirable microflora [11].

The antagonistic effect of the preparation is achieved due to the increase in the acidity level (reduction in pH) due to the formation of a complex of organic acids and the formation of substances in the process of vital activity of the introduced microorganisms, inhibiting the development of undesirable microflora (for example, bacteriocins, antibiotics, peroxides). Due to this effect, it becomes possible to extend the shelf life and preserve the biological value of sausage products [11].

To confirm this position, i.e. to achieve a positive effect from the use of the recommended additive, studies were conducted to compare the microbiological composition of the control sample and two experimental samples of sausage minced meat. The first conclusion from the results of the study was confirmation that, according to the indicators of microbiological contamination, the minced meat of the

experimental composition (test sample) complied with the standards of current regulatory documentation in terms of contamination with pathogenic microorganisms, including bacteria of the genus *Salmonella* and sulfite-reducing clostridia (absence). The total number of mesophilic aerobic and facultative anaerobic microorganisms in the comparison object was within 7×10^5 in one gram of product, and in the experimental samples, their presence was not detected at all. The corresponding indicators are given in **Table 6.8**.

Table 6.8 Results of microbiological analysis of control and experimental samples of sausage minced meat and raw materials used for its production

Sample name	Name of microorganisms			
	Escherichia coli bacteria	micrococci	MAFAM	LAB
Salted beef	Presence in 0.01 g	1×10^3	7.4×10^5	1.8×10^4
Fatty salted pork	Presence in 0.01 g	2.2×10^3	7.3×10^5	1.0×10^4
Low-fat salted pork	Presence in 0.1 g	2.7×10^3	7.2×10^5	5.0×10^4
Control (minced meat)	Presence in 0.01 g	7 × 103	3.1 × 105	4.1×10^4
Experiment 1 (minced meat)	Presence in 0.1 g	7×10^5	Not detected	1.3×10^6
Experiment 2 (minced meat)	Presence in 0.01 g	2×10^5	Not detected	4×10^5
Experiment 1 (sausages)	Presence in 0.001 g	2.2×10^5	Not detected	2.2×10^6
Experiment 2 (sausages)	Presence in 0.001 g	3.2×10^5	Not detected	6.3×10^6

An additional effect of the preparation is the acceleration of the acidification process (reduction of the pH value) of the meat system, which, in addition to contributing to the increase in tenderness and juiciness of the meat. In addition to the microorganisms introduced with the bacterial preparation, an increase in the number of lactic acid bacteria (LAB) responsible for the formation of organic acids in the system (reduction of the pH level) was also recorded in the meat raw material during the aging process of minced meat. The analysis results show that their content in the test samples is higher than in the raw material to which the preparation was not introduced during the entire fermentation period. The dynamics of the increase in their number in ready-to-sell products under stationary conditions is shown in **Fig. 6.6**.

Another, no less important positive aspect of the claimed method of using the bacterial preparation "Iprovit-LRR" is its high denitrifying activity, associated with the growth in the number of lactic acid bacteria of the *L.rhamnosus* strain in minced meat within 48 hours to ($4 \times 10^5 \div 1.3 \times 10^6$) versus 4.1×10^4 at the beginning of its aging. Their vital activity led to a rapid increase in the acidity level of minced meat of

the experimental composition to pH values = 4.8–5.2 versus the corresponding pH indicator of minced meat of the control composition of 6.3 units [22].

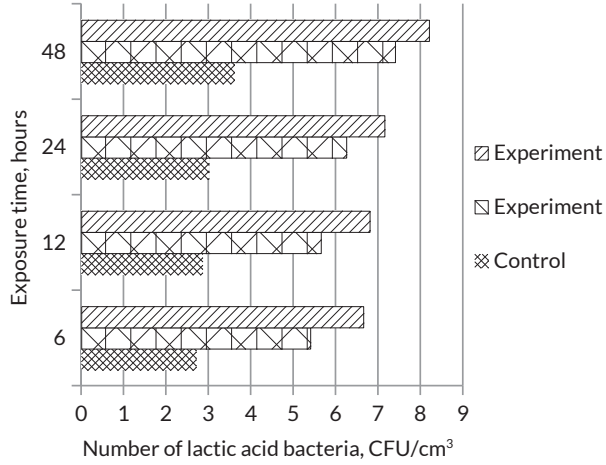


Fig. 6.6 Dynamics of growth of the number of lactic acid bacteria in raw meat

A concomitant effect is the conversion of sodium nitrite, added to preserve the red color of minced meat, into unstable nitrite acid in an acidic environment (pH < 6.0) $NaNO_2$ [11]

$$NaNO_2 + H^+ \rightarrow HNO_2 + Na^+.$$

This acid quickly decomposes to form water and nitric oxide (II) NO, which, according to its intended purpose, prevents the formation of undesirable metmyoglobin in meat and instead participates in the transition of myoglobin to nitrosomyoglobin and thus preserves the usual red color of the meat mixture [11]

$$3\,HNO_2 \rightarrow HNO_3 + 2\,NO + H_2O.$$

Part of the newly formed nitric acid HNO_3 partially dissociates with the entry of nitrate ion NO_3 into the aqueous medium, partially decomposes to form nitrogen dioxide [11]

$$4\,HNO_3 \rightarrow 4\,NO_2 + O_2 + 2\,H_2O.$$

In conditions of a huge amount of water, nitrogen dioxide re-forms two acids in the system: nitric and nitrite [11]

$$2\,NO_2 + H_2O \rightarrow HNO_3 + HNO_2.$$

Ideally, the process under the conditions of dissociation of nitric acid to nitric oxide and its (NO) interaction with meat myoglobin should be repeated until the nitrate ion is completely depleted in the system, however, due to the fact that the acidity of the meat environment remains insufficiently high (pH ≥ 4.8), the absolute majority of the nitrate ion is not decomposed, remains in the minced meat, giving it a high oxidation-reduction potential (ORP) and in the process of sausage production due to insufficiently high processing temperature remains there. As a result, the product is contaminated with an undesirable admixture of sodium nitrate, and part of the sodium nitrite introduced into the meat mixture is lost [11].

At the same time, the cumulative impact on the health of consumers of residues in the product of both salts – nitrite and sodium nitrate – has not been studied, which all the more poses for technologists, in addition to the problem of minimizing the amount of added toxic sodium nitrite additive, the question of finding a way to reduce the amount of sodium nitrate formed in the mass [11].

In our opinion, the problem can be solved at the stage of minced meat production by introducing additives with antioxidant action into the mixture, i.e. those that surpass myoglobin in the ability to absorb active oxygen – either the one that migrates deep into the meat upon contact with air or the one that is formed during the decomposition of nitrate ion [11].

As a substance of similar action in this study, a rosemary extract supplement was used, which contains no less than 29 compounds, including 4.77% of sesquiterpenes characterized by antioxidant activity: 2.1% 1.8-cineole, 0.6% camphor, 0.55% α-pinene, 0.4% β-pinene and rosmarinic acid, characterized by the highest antioxidant properties – 5.5–6.0%, where the attack of oxidants occurs on the double bond C = C of the carbon chain, which connects two cresol cycles.

In determining the optimal dosage, the dynamics of peroxide value changes were investigated over a 10-day storage period in both the control sample of sausage mince (without the addition of rosemary extract) and the experimental samples, to which 0.05%, 0.10%, 0.15%, and 0.20% of the extract were added. The results obtained during the study are presented in **Fig. 6.7**.

Considering the results obtained, it was recommended to introduce the additive into the minced meat in an amount of 0.15% relative to its total mass, since its

further addition did not have a positive effect on the increase in the antioxidant activity of the sample [13].

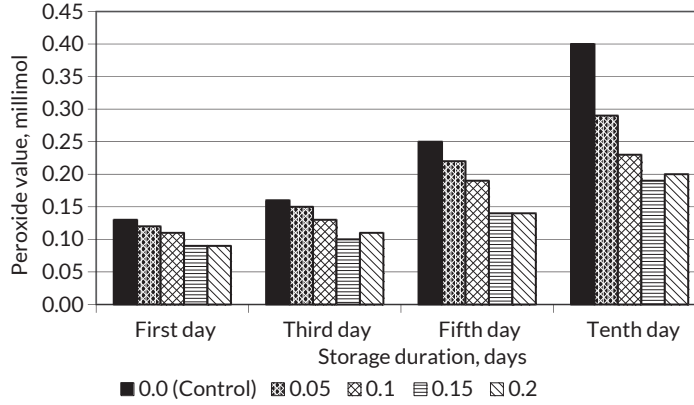


Fig. 6.7 Dynamics of changes in the peroxide value of control and experimental samples of sausages enriched with rosemary extract

An additional action aimed at reducing the dosage of sodium nitrite while ensuring the desired color of the meat mixture is the addition of the orange dietary fiber Citri-Fi 100, characterized by a two-factor effect, to the minced meat at the stage of its formation. In addition to the main function of retaining the increased amount of moisture in the minced meat among all those studied in the work, the largest amount of water is retained by the orange fibers Citri-Fi 100, characterized by a developed surface area and, accordingly, the ability to adsorb [11].

The positive properties of orange dietary fiber supplements include the fact that they contain a large number of phenolic components of flavonoid nature (2.2-azino-bis-3-ethylbenzothiazoline-6-sulfonic acid, 2.2-diphenyl-1-picryldrazyl, 2.2-azo-bis-2-methyl-propanilamide, etc.) characterized by antioxidant activity and, to a certain extent, bactericidal properties [11].

Considering that both additives recommended for use in sausage minced meat are characterized by antioxidant effects, it is possible to study their cumulative effect on the dynamics of peroxide compounds accumulation in minced meat over 10 days. The addition of rosemary extract to minced meat was introduced in the amount of 0.15%, recognized as optimal in previous studies [11].

The experimental data obtained indicate the effectiveness of the proposed additives, characterized by antioxidant activity, in inhibiting by more than half the rate

of formation of substances associated with the presence of reactive oxygen, and thereby in reducing the dosage of sodium nitrite [11].

Thus, all parameters of the composition of the experimental minced meat of the modified composition are, from the point of view of its consumer value and organoleptic properties, better compared to the corresponding properties of meat mixtures where it was not introduced. On this basis, it is possible to conclude that it is appropriate to introduce the preparation "Iprovit LRR" into the developed minced meat recipe with its subsequent aging until full maturation at the temperature +2°C recommended by the Institute of Food Resources of Ukraine for two days [11].

6.3 Determination of functional and technological properties of minced meat systems

The research was conducted on minced meat of improved composition, samples corresponding to the norms of the standard DSTU 4436:2005 "Cooked (boiled) sausages, Sausages, Small Sausages, Meat Loaves" served as control. When assessing the balance of the chemical composition of meat products, priority attention is paid to the qualitative and quantitative analysis of amino acids, which determine the level of protein completeness, and for the characteristics of the biological value of sausages, the most important parameters are their protein quality index and the index of essential amino acids. On this basis, it was faced with the task of developing the composition of sausages, which, along with their health-improving properties, would also be characterized by the completeness of the protein composition. In order to determine the achievement of the set goal in developing a complete protein composition of minced sausage, research was conducted, the results of which are presented in **Table 6.9**.

The data presented indicate that the minced meat of the developed composition contains all eight essential amino acids in quantities that all, without exception, exceed the recommended FAO/WHO content level. A similar phenomenon is observed when comparing the corresponding indicators of the composition of the developed minced meat with that of the standardized national standard DSTU 4436:2005 "Cooked (boiled) sausages, Sausages, Small Sausages, Meat Loaves. General technical requirements". The obtained data indicate the high quality and biological value of the research product.

Each ingredient recommended for inclusion in the composition of the developed minced meat has a significant characteristic effect on their physicochemical indicators. Thus, the use of sea salt, characterized by a reduced content of sodium chloride

and enriched instead with hygroscopic chlorides of potassium and magnesium, as well as fiber and other types of dietary fiber, significantly increases the content of moisture contained in meat mixtures and, therefore, water activity. The use of bacterial preparations contributes to a rapid change in the acidity of the mixture and shortens the aging period of minced meat. The use of blood plasma protein, in addition to enriching the mixtures with this valuable component, also improves their plasticity indices.

Table 6.9 Characteristics of the amino acid composition and biological value of the experimental and control samples

Essential amino acid name	FAO/WHO standard g/100 g of protein [23]	Samples			
		Control		Experiment	
		g/100 g protein	amino acid ratio, %	g/100 g protein	amino acid score, %
Leucine	7	10.0 ± 0.46	142.8	11.4 ± 0.46	162.8
Methionine + cystine	3.5	4.2 ± 0.21	120	4.28 ± 0.22	122.3
Valine	5	6.0 ± 0.26	120	6.6 ± 0.26	132
Lysine	5.5	8.2 ± 0.29	149.1	9.0 ± 0.3	163.6
Threonine	4	6.1 ± 0.21	152.5	7.1 ± 0.21	177.5
Phenylalanine + tyrosine	6	8.1 ± 0.31	135	9.2 ± 0.32	153.3
Tryptophan	1	1.1 ± 0.05	110	1.6 ± 0.05	160
Isoleucine	4	6.1 ± 0.23	152.5	6.5 ± 0.23	162.5
Sum of essential amino acids	36	49.8 ± 2.06		55.6 ± 2.08	

However, the total result of their application due to the complexity of the interaction mechanisms of the mixture components cannot be predicted based on the results of studying the individual influence of each of them. Therefore, in practice, an empirical approach is used to determine the properties of each of the individual mixtures, among which one of the important ones is the ability of minced meat to form emulsions that are stable over time, which are understood as dispersed systems consisting of a liquid dispersion medium and a colloidal dispersed phase. The dispersed phase in such a system is formed by fat particles of different sizes, and the dispersion medium is a solution of proteins and low-molecular substances.

The stability of the emulsion is provided by substances (emulsifiers) that adsorb on the surface of fat droplets and thus prevent their sticking together. These include, for example, protein films that significantly affect the stability of meat emulsions and,

accordingly, the quality of meat products. The fat-protein-water interaction occurs due to the presence of a large number of hydrophilic and hydrophobic groups in protein molecules. Hydrophobic groups form a strong adsorption layer on the outer surface of the droplets, which plays the role of a barrier in preventing fat coalescence. Hydrophilic groups are oriented towards external moisture and form a sufficiently strong network in volume that does not delaminate throughout the entire guaranteed shelf life of the sausage product.

On this basis, the blood plasma protein was used as an agent that should contribute to the formation of minced meat emulsion. The results of the experiment are shown in **Fig. 6.8**.

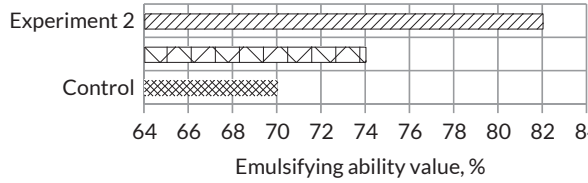


Fig. 6.8 Emulsifying ability of the control and experimental samples of minced meat

Emulsions formed with the participation of blood plasma protein were sufficiently stable the experimental minced meat systems possess an increased, in comparison with the control, ability to form a stable emulsion, which is quantitatively characterized by emulsifying capacity indicators – 82% in Experiment No. 2 versus 70% in the control – and emulsion stability – 96% in the same experiment versus 88% in the control, as presented in **Fig. 6.9**.

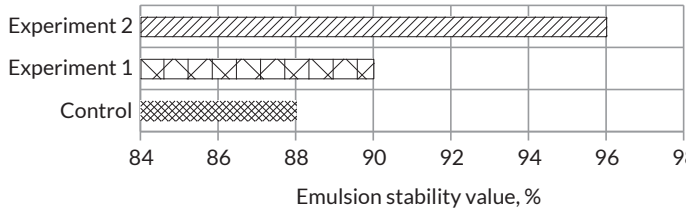


Fig. 6.9 Indicators of emulsion stability of the control and experimental samples

This pattern is explained by the fact that the additives introduced with orange dietary fibers, as well as blood plasma protein, causes high reactivity and reliable binding of the water component. The addition of blood plasma protein also allowed

to improve the plasticity index of the meat emulsion, and the addition of rosemary extract, in addition to enriching the taste and aroma of the finished product, also allowed to extend the period of its guaranteed storage due to certain antioxidant properties (**Table 6.10**).

Table 6.10 Functional-technological and physico-chemical quality indicators of control and experimental samples of meat products

Indicator	Sample name		
	Control	Experimental No. 1	Experimental No. 2
Active acidity, pH units	5.8 ± 0.03	5.6 ± 0.03	5.54 ± 0.03
Mass fraction of moisture, %	75.29 ± 3.11	74.24 ± 3.16	75.44 ± 3.16
Redox potential, mV	140 ± 7.5	−75.3 ± 3.8	−76 ± 3.8
Water activity, A_w	0.952 ± 0.05	0.953 ± 0.05	0.957 ± 0.05
Water binding capacity, % of total mass	85.1 ± 2.31	88.7 ± 2.33	90.2 ± 2.33
Plasticity, cm^2/g	32.9 ± 1.03	37.2 ± 1.03	45.7 ± 1.03
Yield shear stress, Pa	605 ± 30.25	792 ± 39.55	805 ± 39.55

Thus, the specified set of additives allowed to improve the organoleptic and physicochemical properties of the product, primarily with regard to the indicators of plasticity and elasticity of the finished product compared to the corresponding properties of a product of standardized composition.

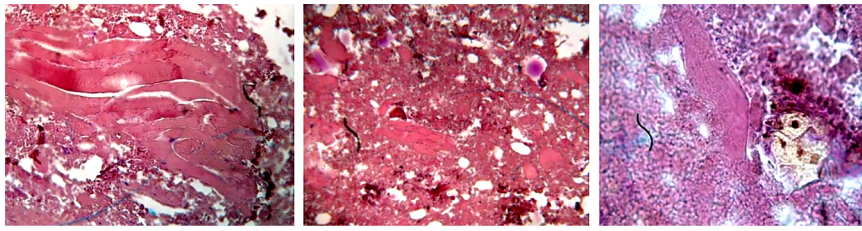
Considering the experimental data, it can be noted that the active acidity of the studied minced meat systems characterizes them as benign. The difference in pH values is explained by the activity of the bacterial preparation and rosemary extract introduced into the formulation of the experimental samples.

It should be noted that the experimental minced meat systems 1 and 2 are characterized by pronounced antioxidant properties since their redox potential is negative and is −75.3 mV and −76 mV, respectively, versus +140 mV in the control.

The moisture content in the tested samples is almost at the same level and is within the error range. The water binding capacity of the tested samples is higher than the control, and is 89.8% and 91.2%, respectively, against 88.8%.

Sausage mince belongs to plastic-viscous bodies therefore its structure and rheological properties are best characterized by the value of the yield shear stress and plasticity. Experimental data indicate the compaction of the mince and the increase in the plasticity of the experimental samples compared to the control. Thus, the yield shear stress of the experimental sample No. 2 is 805 Pa, the plasticity is 45.7 cm^2/g,

and the control sample is 605 Pa and 32.9 cm^2/g, respectively. This is explained by the presence of dietary fiber and blood plasma protein in the recipe, which improve the structural and functional-technological properties of the mince system. An informative characteristic that complements the data on future changes in the consistency of finished products is the microstructure of the stuffing (**Fig. 6.10**).



Control sample Experiment 1 Experiment 2

Fig. 6.10 Microstructural characteristics of the control and experimental minced meat samples (magnification × 400)

The results of the microstructural analysis of the presented samples indicate that the control minced meat has a homogeneous structure of pink color with the inclusion of numerous vacuoles. It shows individual fragments of single muscle fibers, and sometimes entire groups, which are densely located next to each other and cut lengthwise and crosswise. Clusters of fat cells are also found. In most fragments of Experiment No. 1, the nuclei of muscle fibers and transverse striation are not detected. They are observed only in individual fibers. Small particles of yellow color are also found in the minced meat, which indicates the presence of rosemary granules. In another experimental sample, an eosinophilic substance (purple color) is observed in voids and vacuoles of various sizes and configurations (detection of blood plasma). Clusters of round and rectangular plant cells are also found in the minced meat, they have different sizes and shapes, painted in different shades of purple and yellowish colors. This indicates the presence of citrus fibers.

The experimental samples are characterized by a denser and more elastic consistency compared to the control, which is confirmed by an increase in the yield shear stress by 70%. The experimental samples show lower mass losses after heat treatment, compared to the control, as evidenced by an increase in yield by 7%. This effect was achieved without adding a phosphate mixture. The improvement of organoleptic quality indicators is associated with the introduction of fiber and a bacterial preparation into the recipe, which, due to the absorption of added moisture and the reduction of losses of natural moisture by meat raw materials. The chemical

composition of the control sample compared to experimental samples 1 and 2 is given in **Table 6.11**.

Table 6.11 Chemical composition of control and experimental samples of minced meat, %

Component	Sample name		
	Control	Experiment No. 1	Experiment No. 2
Protein	12.3 ± 0.8	13.7 ± 0.7	15.0 ± 0.7
Fat	9.38 ± 1.16	11.49 ± 1.04	12.44 ± 1.04
Humidity	66.7 ± 0.7	69.6 ± 1.3	70.1 ± 1.3
Sodium chloride	1.20 ± 0.10	0.55 ± 0.09	0.41 ± 0.09
Sodium nitrite	0.0044 ± 0.0002	0.0012 ± 0.0002	0.0012 ± 0.0002
Water	0.97 ± 0.01	1.30 ± 0.01	2.20 ± 0.01

According to the requirements of the sausage production regulations, the protein content in the mass should not be less than 12%, and according to this indicator, both the control and experimental samples meet the norm. In terms of the mass fraction of fat, both samples do not deviate from the norm by less than 30%, however, in the experimental samples, according to the results of microscopy, the fat is evenly distributed throughout the entire volume of the product. As for water, the amount of moisture in the samples of the experimental composition due to the uniform distribution of blood plasma protein and fiber in the structure of the meat system exceeds the corresponding indicator of the sample of the control composition by 4.6%. The chloride and sodium nitrite content in all samples does not exceed the requirements set by regulatory documents. At the same time, the use of components with antioxidant and preservative effects reduced the content of toxic nitrite ion in the experimental samples by 0.032%, and the use of sea salt instead of ordinary table salt allowed while maintaining the desired level of product saltiness, to reduce the content of sodium ion in the experimental products.

Organoleptic evaluation of sausages of the control and experimental samples of sausage minced meat (Experimental No. 2) was carried out in the laboratory of the Department of Meat, Fish and Seafood Technology of the NULES of Ukraine. The evaluation of the samples was carried out according to the indicators regulated in DSTU 4436:2005 "Cooked (boiled) sausages, Sausages, Small Sausages, Meat Loaves". The evaluation results are given in **Table 6.12**.

According to the results of the organoleptic evaluation, the quality indicators of both experimental samples were better compared to the control, and the results of their evaluation according to the scoring system are shown in **Fig. 6.11**.

Table 6.12 Results of evaluation of organoleptic quality indicators of sausages of control and experimental samples

Indicator	Sample name	
	Control	Experiment No. 2
Appearance	Sausages with a clean, dry surface, no damage to the casing, slight broth swellings are present	Sausages with a clean, dry surface, without damage to the casing, the latter tightly adhering to the minced meat, without broth swellings
Consistency	Elasticity is reduced in the peripheral part	Dense on section, both in the periphery and in the center
Cutaway view	The minced meat is grey-pink, the color is heterogeneous, there are grey spots and relatively large cavities	The minced meat is pink, uniform, without large cavities and gray spots
Smell and taste	Inherent to this product but implicitly expressed, the saltiness is uneven, without foreign odors and flavors	Typical for this product, the saltiness is uniform, there are no foreign tastes or odors

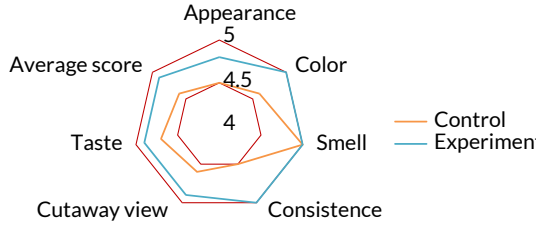


Fig. 6.11 Results of organoleptic evaluation of quality indicators of control and experimental (No. 2) sausage samples

A comprehensive analysis of the organoleptic evaluation shows that the test sample was distinguished by a denser, elastic and homogeneous consistency. It was also characterized by a pleasant "deep" taste and noble aroma, which can be explained by a more intensive accumulation of free amino acids during the salting process under the influence of lactic acid microflora. The tasting commission also noted a moderately pronounced, delicate, natural color on the cut of the test samples.

6.4 Development of a technology for the production of "Ozdorovchi" sausages using biotechnological techniques

According to the results of the conducted experimental work on the study of the influence of antioxidants, dietary fiber, salt with a reduced sodium content and

bacterial preparation on the properties of minced meat systems and the justification of the feasibility of their use in the technology of sausage products, a recipe for "Ozdorovchi" sausages was developed (**Table 6.13**).

The recipe and quantity of substances used in the preparation of brine for salting meat raw materials are given in **Table 6.14**.

Table 6.13 Recipe for minced meat of experimental sausage samples

Raw material name	Norm
Unsalted raw material (kilograms per 100 kg of raw material)	
Beef, trimmed, first category	30
Semi-fat trimmed pork	26
Fatty trimmed pork, cheek, fat cuts	34
Blood plasma protein	1.0
Water for blood plasma protein hydration	2.0
Fiber (Citrus fiber Citri-Fi 100)	0.5
Water for fiber hydration	6.5
Total	100
Spices and materials (grams per 100 kg of raw materials)	
Sea salt with laminaria	2100
Granulated sugar	160
Sodium nitrite	5.0
Ground black or white pepper	160
Ground allspice	100
Ground nutmeg or cardamom	50.0
Bacterial preparation "Iprovit-LRR"	50.0
Rosemary extract	15.0
Water (kilograms)	30.0

Table 6.14 Brine recipe for salting raw meat (kg/100 kg)

Ingredient	Sample name
Sea salt with laminaria	2.1
Granulated sugar	0.1
Water	6.3
Total	8.55

The process consisted of: receiving raw materials, defrosting and primary grinding, soaking in a salting mixture, which contains a bacterial preparation "Iprovit-LRR", combining the minced meat and processing it in a cutter, shaping, settling, heat treatment, and cooling, characterized as follows [24].

A characteristic feature of the proposed technology is the addition of 35–40% of ice from the mass of the ground raw material to the cutter during the meat grinding process and the introduction of dietary fiber, health-improving and antioxidant additives into the minced meat. The previously ground raw fat was added to the cutter at the stage of grinding the fatty raw material. The minced meat was formed into casings by injection molding at a residual pressure of $P = 0.8 \times 10^4$ Pa. The filled casing was shaped in the form of bars using special devices. The sausages were separated from each other, tied with twine and hung on sticks with an interval between the bars to prevent sticking, placed on frames and sent for heat treatment. Smoke for frying sausages was obtained by burning dry logs from hardwood trees in smoke generators. In universal heat chambers, sausages were dried and fried until the surface turned red for 30…50 minutes at a temperature of 90…100°C on the surface of the loaves and reaching a temperature in the center of the workpiece of not less than 55°C and for 5…10 minutes, they were treated in universal heat chambers with steam at 85…90°C and a relative humidity of 85…90% until the temperature in the centre of the bar reached 70 ± 1°C. After cooking, the sausages were cooled under a cold water shower for 6…10 minutes, then in a chamber at a temperature not higher than 8°C until the temperature in the center of the bar reached 0…15°C [13].

The sausage composition developed based on the results of the work performed is standardized by the technical specifications of the technical specifications. IN 10.1-00493706-064:2019 "Ozdorovchi sausages".

6.5 Conclusions

The effectiveness of using the following ingredients in sausage technology has been confirmed: bacterial preparation "Iprovit LRR", sea salt with a reduced sodium chloride content and the addition of laminaria extract; orange dietary fiber Citri-Fi 100 of preventive action with the content of biologically active flavonoids, citral and lemon; blood plasma proteins; rosemary extract.

The functional and technological properties of minced meat systems of the developed composition were studied. It was shown that the content of essential amino acids in minced meat of the developed composition is higher compared to the

corresponding characteristic of minced meat of the standard composition. A similar advantage of the experimental samples was shown in terms of plasticity, yield shear stress and water binding ability. Comparison of the appearance and organoleptic properties of the developed product with the corresponding characteristics of the sample of the standardized composition showed the superiority of the experimental minced meat in all the studied indicators.

A recipe for minced meat for the experimental sample of minced sausages "Ozdorovchi" was developed with the inclusion of blood plasma protein, dietary citrus fibers and rosemary extract, as well as brine for its salting, where instead of rock salt, it is recommended to add a slightly smaller amount of sea salt and granulated sugar to the brine.

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CHAPTER 7

Optimization of goose meat quality through oat and alfalfa-based feed additives

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Abstract

This article presents the results of a study dedicated to examining the effects of incorporating vegetative parts of oats (*Avena sativa L.*) and alfalfa (*Medicago sativa L.*) into the diet of Legard Danish breed geese on the physico-chemical, biochemical, and nutritional properties of the meat, particularly its oxidative stability, fatty acid, and amino acid composition. Two groups of geese were formed for the experiment. The control group received a standard diet consisting of compound feed and green mass dominated by knotweed (*Polygonum aviculare L.*). In the experimental group, 50% of the green mass was replaced with a mixture of vegetative parts of oats and alfalfa in equal proportions. Goose meat was stored for 90 days at a temperature of −18°C.

The research findings indicate that feeding oats and alfalfa had a positive impact on the technological properties of the meat. In particular, the experimental group showed improved water-holding capacity and reduced weight loss during thawing, directly related to better water retention in muscle fibers. These indicators are important for both consumer attributes and industrial meat processing. Special attention was given to evaluating the intensity of lipid peroxidation. It was found that the meat of the experimental group had a lower level of primary lipid peroxidation products on the 45th day of storage. This trend indicates the inhibition of oxidative processes under the influence of phytonutrients, particularly avenanthramides, oxylipins, and polyphenols present in oats and alfalfa. An increase in vitamin E and β-carotene content was observed throughout the storage period, suggesting the ability of bioactive feed components to be deposited in poultry tissues and preserved even during long-term low-temperature storage. The fatty acid composition of the goose meat from the experimental group was enriched with mono- and

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polyunsaturated fatty acids. An increase in oleic acid content was noted in the experimental group on the 90th day. Optimization of the ω-6/ω-3 polyunsaturated fatty acid ratio was also established, which is a positive trait in terms of food safety and product functionality. The amino acid profile of the meat from the experimental group showed an increase in essential amino acids such as leucine, isoleucine, and phenylalanine. These changes indicate an increase in the biological value of muscle protein, which is significant for rational human nutrition.

Keywords

Geese, meat, alfalfa, oats, antioxidants, fatty acids, amino acids, vitamins, lipid peroxidation, meat quality.

7.1 Modern approaches to improving goose meat quality using natural-origin strategies

Poultry meat, particularly that of waterfowl, is considered one of the most valuable components of human nutrition due to its high nutrient density, biologically complete proteins, optimal content of vitamins and minerals, and relatively low-fat content. Among the key micronutrients found in meat are iron, zinc, phosphorus, potassium, magnesium, calcium, sodium, and others, which makes this product an essential element of the diet in the context of growing nutritional imbalance [1].

Over the past decades, there has been a steady increase in global demand for poultry meat. According to analytical reports, global production of this commodity is projected to exceed 145 million tons by 2029, driven not only by its nutritional value but also by its economic affordability [2]. At the same time, external challenges – such as the COVID-19 pandemic, disruptions in supply chains, and armed conflicts, particularly the war in Ukraine – have adversely affected the stability of agri-food production in general and the poultry sector in particular [3]. These developments have underscored the need for effective recovery of the industry based on locally available resources adapted to current realities.

Goose farming, as a segment of the poultry industry, possesses considerable potential in the context of expanding meat production and diversifying meat products. Geese demonstrate a high efficiency in utilizing pasture-based feed, exhibit strong resilience, and require relatively low rearing costs, making them particularly attractive for small and medium-sized farming enterprises. The development of goose farming may also serve as a component of food security strategies in regions with limited capacity for intensive agricultural production.

Despite the high nutritional value of goose meat, the issue of its stability during storage remains unresolved. It is well established that goose meat contains elevated levels of unsaturated fatty acids – particularly linoleic (C18:2 n-6), linolenic (C18:3 n-3), oleic (C18:1 n-9), and arachidonic (C20:4 n-6) acids – which are susceptible to oxidative degradation during prolonged storage [4]. This deterioration negatively affects both the organoleptic properties of the product (color, odor, taste, texture) and its biological value and safety for consumers [5]. Lipid oxidation, as a non-microbial form of spoilage, is considered the primary factor contributing to the decline in meat quality under low-temperature storage conditions [6].

Currently, two primary strategies are employed to enhance the antioxidant stability of meat: the use of exogenous antioxidants (as additives to raw meat) and the modification of poultry diets through the inclusion of natural sources of bioactive compounds. While the incorporation of plant and spice extracts – such as clove, cumin, and ginger – has proven effective [7], the use of natural feed-based ingredients is considered more economically viable and technologically feasible under commercial production conditions.

According to the literature, promising natural dietary components include oat (*Avena sativa*) and alfalfa (*Medicago sativa*). These plants are rich in antioxidant phytochemicals such as avenanthramides, tocopherols, and phenolic acids, and are notable for their high content of dietary fiber, proteins, and essential amino acids [8, 9]. However, their use as feed ingredients for waterfowl, particularly geese, remains insufficiently studied in terms of their impact on meat quality during storage.

In the context of current challenges related to food security, the search for biologically sound methods to extend the shelf life of meat products and improve their nutritional quality, studies aimed at evaluating the effects of oat and alfalfa on goose meat parameters are of considerable scientific and practical significance.

The aim of this study is to enhance the quality characteristics of goose meat and ensure their stability during long-term frozen storage by enriching the birds' diet with vegetative parts of oat (*Avena sativa*) and alfalfa (*Medicago sativa*).

To achieve the stated objective, the following tasks were defined:

– to determine the main slaughter parameters of geese in the control and experimental groups;

– to analyze the physicochemical properties of meat during 90-day low-temperature storage;

– to assess biochemical indicators that characterize the stability of meat raw material during storage.

7.2 Materials and methods of the study

The research hypothesis was as follows: the inclusion of feed components enriched with natural antioxidants – specifically, oat and alfalfa – into the diet of Legart Danish geese would inhibit lipid peroxidation processes in meat. This intervention is expected to lead to a reduction in the concentration of lipid peroxidation products (LPO) and an improvement in the fatty acid profile. Furthermore, due to the high nutritional value and phytochemical composition of these feed additives, an increase in the content of fat-soluble vitamins, as well as essential fatty acids and amino acids, in goose meat is anticipated.

Within the framework of the experiment, two groups of geese, each consisting of five birds, were formed. The control group (C) received a standard diet based on compound feed and green forage, primarily composed of knotgrass (*Polygonum aviculare L.*). In the experimental group (E), 50% of the green forage was replaced with a mixture of oat and alfalfa in equal proportions. This dietary modification was applied from day 7 to day 62 of rearing. Slaughter was performed on day 63, after which the slaughter performance indicators were evaluated.

After slaughter, the goose carcasses underwent a standard technological process, which included exsanguination, thermal treatment (scalding at 70–75°C), feather and viscera removal, washing, portioning, and chilling at a temperature of 0–1°C.

Subsequently, the meat from both groups was stored for 90 days at a temperature of –18°C. During this storage period, analytical assessments were conducted to evaluate key quality parameters, including: pH (acidity), moisture content, protein and fat levels, water-holding capacity, thawing loss, levels of lipid peroxidation products (LPO), concentrations of vitamins E, A, and β-carotene, as well as the amino acid and fatty acid profiles. All measurements were carried out on samples of breast meat.

Moisture content in the meat was determined by drying weighed samples in drying dishes.

Protein content was analyzed using a photocolorimetric method [10].

The amount of intramuscular fat was assessed by extraction using a Soxhlet apparatus with chloroform as the solvent. Water-holding capacity (WHC) was evaluated based on the amount of water released from a 300 mg sample during 10 minutes of pressing under a 1 kg load [11].

Lipid oxidation processes in the meat were evaluated by determining substances reactive with 2-thiobarbituric acid (thiobarbituric acid reactive substances, TBARS) [11].

The fatty acid composition was analyzed using gas-liquid chromatography [12].

Vitamin E was determined spectrophotometrically based on its ability to reduce Fe^{3+} to Fe^{2+}, which forms colored complexes with 2.2′-dipyridyl [13].

Vitamin A content was measured based on the formation of a blue complex with boron trifluoride ($C_4H_{10}OBF_3$) [13].

β-carotene was quantified using a photocolorimetric method by measuring its intrinsic absorbance at 450 nm [13].

Amino acid composition was determined using ion-exchange liquid-column chromatography with an automatic amino acid analyzer T 339 (Czech Republic) [14].

Data analysis was performed using SPSS software version 17 (USA) and Microsoft Excel 2013 (USA), applying Student's t-test for statistical evaluation [15].

7.3 Results and discussion

The study revealed a gradual decrease in moisture content in the breast meat of both the control and experimental groups over the 90-day storage period (**Fig. 7.1**). The total reduction in moisture content amounted to 8% ($p \leq 0.01$) in the control group and 7.3% ($p \leq 0.01$) in the experimental group. Beginning from day 45 of storage, the breast meat of the geese in the experimental group exhibited a statistically significantly higher moisture level compared to the control group ($p \leq 0.05$), indicating an improved ability of the muscle tissue to retain moisture under freezing conditions.

During the first 45 days of storage, the breast meat of geese in the experimental group exhibited a higher protein content compared to the control group: specifically, by 5.3% on day 1 ($p \leq 0.05$), 5.2% on day 23 ($p \leq 0.05$), and 5.7% on day 45 ($p \leq 0.05$). This effect may be attributed to the high content of readily digestible proteins in alfalfa and oat, which promotes the accumulation of structural proteins in muscle tissue. Studies on geese have demonstrated that the inclusion of alfalfa silage in the diet enriches the feed with amino acids and biologically active compounds. This contributes to improved metabolic activity, enhanced digestion and nutrient absorption, reduced fat deposition, and increased muscle mass gain [16].

The intramuscular fat content remained relatively stable throughout the entire storage period in both groups, indicating that the inclusion of oat and alfalfa in the diet did not negatively affect the intramuscular fat levels in goose meat. Hwang et al. reported similar findings, where intensive feeding with alfalfa did not result in significant changes in fat content in goat meat [17].

Throughout the 90-day storage period, the pH level of goose breast meat remained stable in both groups (**Table 7.1**). The differences between the control and experimental groups were not statistically significant, indicating that dietary

modifications had no notable effect on the acid-base status of muscle tissue. The recorded pH values were within the physiological range typical for waterfowl meat. Maintaining a normal pH level is critical for meat quality, as excessively low pH may lead to the development of PSE (pale, soft, exudative) defects, which are associated with increased moisture loss and diminished product quality [18].

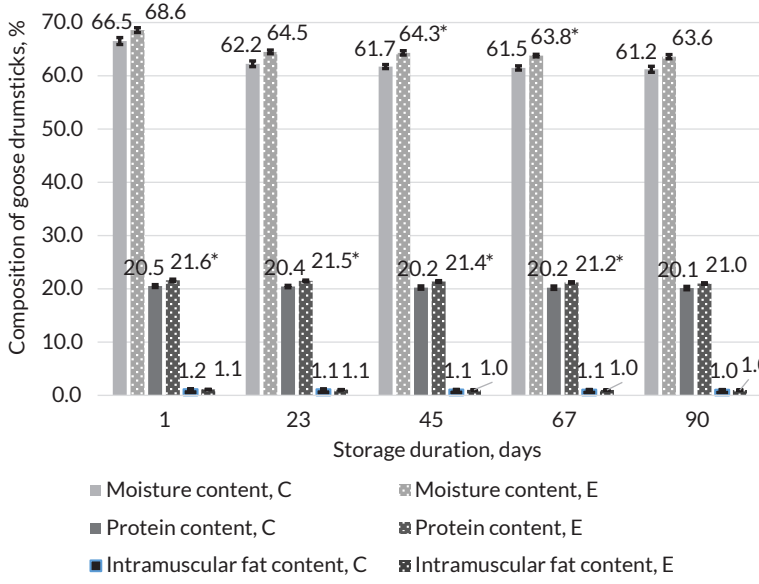

Fig. 7.1 Chemical composition of goose breast meat ($M \pm m$, $n = 5$)
*Note: here and below, differences are statistically significant relative to the control group: * $p \leq 0.05$; ** $p \leq 0.01$*

Table 7.1 Physicochemical parameters of the studied goose breast samples ($M \pm m$, $n = 5$)

Storage duration, days	pH		Thawing loss, %		WHC, %	
	C	E	C	E	C	E
1	6.3 ± 0.01	6.32 ± 0.01	–	–	87.6 ± 1.07	92.2 ± 1.11
23	6.29 ± 0.01	6.32 ± 0.01	2.41 ± 0.08	2.13 ± 0.07*	76.8 ± 1.49	84.7 ± 0.6
45	6.27 ± 0.01	6.31 ± 0.01	2.76 ± 0.05	2.42 ± 0.07*	73.1 ± 1.09	81.1 ± 0.64*
67	6.27 ± 0.01	6.31 ± 0.01	2.81 ± 0.05	2.51 ± 0.05*	70.6 ± 1.46	79.3 ± 0.85*
90	6.26 ± 0.01	6.3 ± 0.01	2.95 ± 0.05	2.64 ± 0.07	70.8 ± 1.68	78.6 ± 1.36*

Throughout the entire storage period, thawing losses increased progressively; however, the values of this parameter consistently remained statistically lower in the experimental group. The most pronounced difference was recorded on day 45 of storage, when moisture loss in the experimental group was 12.3% lower ($p \leq 0.05$), indicating superior structural integrity of the muscle tissue. This effect may be attributed to the influence of phytonutrients present in oat and alfalfa, which positively affect muscle structure and contribute to improved moisture retention.

The water-holding capacity was consistently higher in the experimental group throughout the entire study period. From day 23 onward, a gradual decline in WHC was observed in both groups; however, the values remained higher in the experimental group. The greatest difference was recorded on day 67 of storage, reaching 12.4% ($p \leq 0.05$). This indicates superior hydration capacity in the meat of geese fed a diet supplemented with oat and alfalfa. Improved water-holding capacity contributes to reduced water loss during cryopreservation and subsequent thawing. During freezing, water within the meat crystallizes, which can cause mechanical damage to muscle structures and promote dehydration upon thawing. However, when WHC is maintained at a high level, the structural integrity of muscle fibers is better preserved, minimizing moisture and mass losses in the final product after defrosting.

The study established that, throughout the entire storage period, a gradual accumulation of end products of lipid peroxidation was observed in the meat of both goose groups (**Fig. 7.2**). However, the intensity of this process differed significantly between the control and experimental samples.

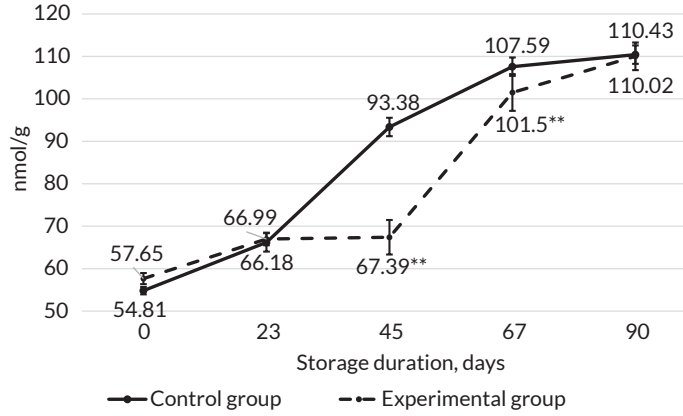

Fig. 7.2 Dynamics of end-products accumulation from lipid peroxidation in goose breast meat during storage ($M \pm m$, $n = 5$)

In the meat of the control group, the concentration of lipid peroxidation end products increased rather intensively. The most pronounced rise was observed between days 23 and 45, with an increase of 41.1%, followed by a further 15.2% increase between days 45 and 67 ($p \leq 0.01$). During the remainder of the storage period, the level of lipid peroxidation products in the control group remained relatively stable.

At the beginning of storage and up to day 23, the level of lipid peroxidation products in the meat of the experimental group did not differ significantly from that of the control group. However, the subsequent dynamics showed a noticeable slowdown in the accumulation of secondary oxidation products, which may indicate activation of antioxidant defense mechanisms within the tissues. The most pronounced difference between groups was observed on day 45 of storage, when the concentration of lipid peroxidation products in the experimental group was 27.8% lower than in the control samples ($p \leq 0.01$). This suggests stabilization of oxidative processes and prolonged maintenance of the prooxidant–antioxidant balance. From day 45 to day 67, an increase in peroxidative activity was noted in the meat of the experimental group, with LPO product levels rising by 50.6% ($p \leq 0.01$). By the end of the storage period, LPO levels in both groups had nearly equalized, indicating a gradual depletion of the antioxidant capacity in the tissues of the experimental group.

The results obtained indicate that the inclusion of oat and alfalfa in the diet of geese contributes to the prolongation of the stabilization phase of the prooxidant-antioxidant balance during meat storage [19]. This effect may be attributed to the high content of natural antioxidants in oat and alfalfa, such as phenolic compounds, tocopherols, and carotenoids, which are capable of neutralizing free radicals and slowing down lipid oxidation processes [20]. It has been established that the antioxidant activity and the qualitative composition of nutrients entering the animal's body largely depend on the formulation of the feed ration and the bioavailability of biologically active substances (BAS) [21]. The observed changes in the dynamics of lipid peroxidation end products in the meat of experimental animals are likely associated with the presence of avenanthramides, polyphenolic compounds, flavonoids, and other BAS, which were introduced into the organism through oat- and alfalfa-based feeds. These compounds have a direct influence on the biochemical properties of the tissue and enhance the biological value of the meat product [22].

The fatty acid composition (FAC) of goose meat underwent significant changes following the inclusion of vegetative parts of oat and alfalfa in the diet (**Table 7.2**). At the time of slaughter, the breast meat of the experimental group showed a higher content of linoleic acid (18:2 $\omega 6$) by 21.1% ($p \leq 0.01$), linolenic acid (18:3 $\omega 3$) by 15.6% ($p \leq 0.01$), and docosahexaenoic acid (22:6 $\omega 3$) by 12.7% ($p \leq 0.01$). The total content of $\omega 3$ polyunsaturated fatty acids (PUFAs) in the breast meat of the

experimental group was 13.9% higher ($p \leq 0.01$). At the same time, the level of arachidonic acid (20:4 $\omega 6$) in the experimental group was 26.9% lower compared to the control ($p \leq 0.01$).

After 90 days of low-temperature storage, a decrease in the content of oleic acid (18:1) by 13.1% ($p \leq 0.01$), linolenic acid (18:3 $\omega 3$) by 21.3% ($p \leq 0.01$), and docosahexaenoic acid (22:6 $\omega 3$) by 10.4% ($p \leq 0.01$) was observed in the meat of the control group. In contrast, these values were higher in the experimental samples by 15.8% ($p \leq 0.01$), 25.3% ($p \leq 0.01$), and 10% ($p \leq 0.01$), respectively. However, the content of arachidonic acid (20:4 $\omega 6$) in the experimental group remained 19.1% lower than in the control ($p \leq 0.01$). By the end of the storage period, the total $\omega 3$-PUFA content in the meat of the experimental group did not significantly differ from that of the control. Nonetheless, the $\omega 6$-PUFA content was 9.9% lower than the corresponding value in the control group ($p \leq 0.05$), which highlights a more optimal $\omega 6/\omega 3$ ratio from a nutritional standpoint [23].

Table 7.2 Dynamics of fatty acid content (ω, %) in goose breast meat from the control (C) and experimental (E) groups during storage ($M \pm m$, $n = 3$)

Fatty acid	Storage duration, days			
	1		90	
	C	E	C	E
(16:0)	23.3 ± 0.82	24.3 ± 0.85	22.8 ± 0.98	23.0 ± 0.83
(18:0)	13.6 ± 0.53	13.0 ± 0.34	13.9 ± 0.54	13.2 ± 0.38
(18:1)	34.0 ± 1.36	32.4 ± 1.23	29.6 ± 1.30	34.2 ± 1.51**
(18:2) $\omega 6$	13.5 ± 0.55	16.4 ± 0.69	18.1 ± 0.54	17.1 ± 0.77
(18:3) $\omega 3$	0.49 ± 0.02	0.56 ± 0.03	0.38 ± 0.02	0.48 ± 0.01
(20:4) $\omega 6$	9.0 ± 0.31	6.6 ± 0.26**	7.7 ± 0.29	6.2 ± 0.25**
(22:6) $\omega 3$	0.67 ± 0.02	0.76 ± 0.03**	0.60 ± 0.04	0.66 ± 0.03*
SFA	39.5 ± 1.43	39.8 ± 1.28	39.2 ± 1.61	38.1 ± 1.28
UFA	60.4 ± 2.35	60.0 ± 2.35	59.8 ± 2.32	61.8 ± 2.69
MUFA	36.3 ± 1.44	35.3 ± 1.33	31.9 ± 1.38	36.5 ± 1.60**
PUFA	24.1 ± 0.91	24.7 ± 1.02	27.8 ± 0.94	25.3 ± 1.09*
$\omega 3$PUFA	1.16 ± 0.04	1.32 ± 0.06	1.54 ± 0.07**	1.58 ± 0.04
$\omega 6$PUFA	22.5 ± 0.86	22.9 ± 0.95	26.2 ± 0.85	23.6 ± 1.03*

The changes observed in the fatty acid composition of breast meat in the experimental group are likely attributable to the influence of compounds with antioxidant

activity [5]. Oat is known to be a rich source of various antioxidants, including β-glucan, avenanthramides, polyphenolic compounds, flavonoids, and β-carotene. Due to their properties, these compounds can effectively inhibit lipid oxidation processes in meat, thereby contributing to the stabilization of unsaturated fatty acids. In addition, the modification of the fatty acid profile may be explained by the high content of linoleic and linolenic acids present in both oat and alfalfa [8]. These essential fatty acids are readily absorbed by the goose organism, which likely played a role in the altered lipid profile of muscle tissue [24]. The increased concentration of ω-3 polyunsaturated fatty acids in goose meat after storage at low temperatures may also indicate the preserved activity of relevant enzymes, particularly desaturases [25].

An analysis of fat-soluble vitamin content in goose breast meat (**Fig. 7.3**) revealed a positive effect of including oat and alfalfa in the geese's diet on the levels of vitamin E and β-carotene. On day 1 of the experiment, the vitamin E content in the meat of the experimental group exceeded that of the control group by 17.1% ($p \leq 0.01$). After 90 days of storage, the vitamin E level in the control group's meat had decreased by 10.6% ($p \leq 0.01$), whereas the meat from the experimental group retained a 13.6% higher concentration of vitamin E ($p \leq 0.01$).

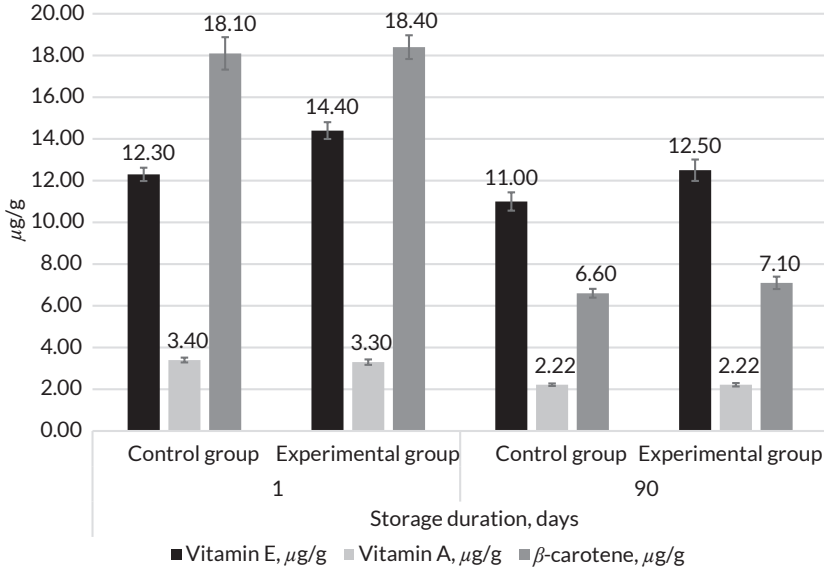

Fig. 7.3 Dynamics of vitamin E, A, and β-carotene content (μg/g) in goose breast meat from the control (C) and experimental (E) groups during storage ($M \pm m$, $n = 3$)

At the beginning of the experiment, β-carotene content was high in both groups. However, after 90 days of storage, a significant decline was observed – by 63.5% ($p \leq 0.01$) in the control group's meat and by 61.4% ($p \leq 0.01$) in the experimental group. Nevertheless, by the end of the study, the β-carotene level in the experimental meat sample remained 7.6% higher than in the control ($p \leq 0.05$).

The increased concentrations of vitamin E and β-carotene in the muscle tissue of geese in the experimental group are likely attributable to the elevated levels of these nutrients in oat, which served as a dietary source for the birds [8]. The higher content of vitamin E and β-carotene in the breast meat of the experimental group on day 90 of storage may also be explained by the antioxidant activity of bioactive compounds found in oat, particularly avenanthramides, which inhibit the intensity of oxidative processes in tissue [26]. The primary cause of β-carotene loss during storage is both enzymatic and non-enzymatic oxidation [27]. The inclusion of oat and alfalfa in the geese's diet did not affect the dynamics of vitamin A content in muscle tissue [19].

The inclusion of oat and alfalfa in the geese's diet resulted in alterations in the amino acid composition of breast meat (**Table 7.3**). On day 1 of the experiment, the meat of the experimental group showed a statistically significant increase in arginine content by 27.5% ($p \leq 0.01$), hydroxyproline by 77.4% ($p \leq 0.01$), leucine by 13.3% ($p \leq 0.05$), and isoleucine by 9.4% ($p \leq 0.05$), compared to the control group. However, the content of methionine and tyrosine was lower – by 66.7% and 45.1%, respectively ($p \leq 0.01$).

Table 7.3 Dynamics of amino acid content (mg/100 g) in goose breast meat from the control (C) and experimental (E) groups during storage ($M \pm m$, $n = 3$)

Amino acid	Storage duration, days			
	1		90	
	C	E	C	D
1	2	3	4	5
Lysine	1.40 ± 0.05	1.46 ± 0.04	1.61 ± 0.05	1.57 ± 0.07
Histidine	0.41 ± 0.02	0.40 ± 0.02	0.27 ± 0.01	0.27 ± 0.01
Arginine	0.90 ± 0.03	1.15 ± 0.04**	0.99 ± 0.04	1.10 ± 0.04*
Hydroxyproline	0.62 ± 0.02	1.10 ± 0.03**	0.69 ± 0.03	0.67 ± 0.02
Aspartic acid	1.18 ± 0.04	1.17 ± 0.04	0.92 ± 0.02	1.06 ± 0.04**
Threonine	0.65 ± 0.03	0.57 ± 0.02*	0.25 ± 0.01	0.23 ± 0.01
Serine	0.58 ± 0.02	0.52 ± 0.02	0.40 ± 0.01	0.34 ± 0.01*
Glutamic acid	2.66 ± 0.08	2.60 ± 0.09	2.25 ± 0.10	2.57 ± 0.10*
Proline	0.55 ± 0.02	0.52 ± 0.02	0.79 ± 0.02	0.72 ± 0.03

Continuation of Table 7.3

1	2	3	4	5
Glycine	0.70 ± 0.03	0.74 ± 0.02	0.93 ± 0.04	0.82 ± 0.02*
Alanine	0.90 ± 0.03	0.95 ± 0.04	1.36 ± 0.06	1.21 ± 0.03*
Cystine	0.29 ± 0.01	0.25 ± 0.01*	0.17 ± 0.01	0.16 ± 0.00
Valine	0.60 ± 0.02	0.62 ± 0.02	0.68 ± 0.02	0.64 ± 0.02
Methionine	0.24 ± 0.01	0.08 ± 0.01**	0.12 ± 0.01	0.08 ± 0.01**
Isoleucine	0.71 ± 0.03	0.78 ± 0.02*	0.70 ± 0.03	0.67 ± 0.02
Leucine	1.25 ± 0.03	1.42 ± 0.04*	1.50 ± 0.04	1.90 ± 0.06**
Tyrosine	0.41 ± 0.01	0.22 ± 0.01**	0.30 ± 0.01	0.32 ± 0.01
Phenylalanine	0.64 ± 0.02	0.66 ± 0.03	0.34 ± 0.01	0.52 ± 0.02**

After 90 days of storage, significant changes in the amino acid composition were observed in both meat samples. In the breast meat of the experimental group, higher levels of several essential amino acids were recorded – specifically, leucine and phenylalanine increased by 25.5% ($p \leq 0.01$) and 51.3% ($p \leq 0.01$), respectively. Additionally, arginine content was 11% higher ($p \leq 0.01$) compared to the control group. At the same time, methionine content remained 33.4% lower ($p \leq 0.01$) in the breast meat of the experimental group.

The observed changes in amino acid composition are likely attributable to differences in the birds' diets, as it is well established that the inclusion of alfalfa in poultry feed enhances protein quality, reduces fat and cholesterol content, and improves the antioxidant potential of chicken meat [28]. Additionally, oat is known for its high content of essential amino acids, which may further contribute to the increased concentrations of these compounds in goose meat [29].

7.4 Conclusions

The inclusion of vegetative parts of oat (*Avena sativa*) and alfalfa (*Medicago sativa*) in equal proportions in the diet of geese exerts a multifactorial positive effect on meat quality under conditions of prolonged low-temperature freezing. This feeding strategy contributes to the preservation of the functional and technological properties of muscle tissue and the optimization of its chemical composition.

The physicochemical properties of meat from the experimental group demonstrated enhanced resistance to alterations induced by freezing and thawing processes. Over the 90-day storage period, the meat exhibited higher water-holding capacity and lower

thawing loss compared to the control group. These findings indicate superior structural stability of the muscle tissue and better preservation of its moisture-retention ability.

At the early stages of storage, the meat of geese from the experimental group exhibited a higher protein content, which can be attributed to the increased bioavailability of amino acids and proteins present in oat and alfalfa. These nutrients likely contributed to the formation and accumulation of protein structures within the muscle tissue.

An analysis of lipid peroxidation processes revealed an antioxidant effect of the dietary modification. In the meat of geese from the experimental group, a statistically significant suppression of oxidative processes was observed, particularly on day 45 of storage, when the content of lipid peroxidation products was 27.8% lower ($p \leq 0.01$). This effect is likely attributable to the influx of biologically active compounds into the tissues, including tocopherols, avenanthramides, polyphenols, and carotenoids.

The inclusion of oat and alfalfa in the geese's diet led to a modification of the fatty acid profile of the meat. An increase in ω-3 polyunsaturated fatty acids (linolenic and docosahexaenoic acids) was observed, along with a reduction in ω-6 PUFA levels, particularly arachidonic acid. This shift contributes to the optimization of the $\omega 6/\omega 3$ ratio, which is important for preventing metabolic disorders in humans.

The content of vitamin E and β-carotene in the meat of the experimental group was significantly higher both at the beginning of the experiment and at the end of the storage period. This indicates effective accumulation and retention of antioxidant compounds within the tissue, enhancing the meat's resistance to oxidative spoilage.

The amino acid profile of goose meat from the experimental group was characterized by elevated levels of several essential amino acids, particularly arginine, leucine, and phenylalanine. This contributes to an increase in the biological value of the meat and enhances its functional potential as a nutritious food product.

Thus, the use of oat and alfalfa in the diet of geese represents a rational biotechnological approach that enables the prolongation of the prooxidant–antioxidant equilibrium and the deceleration of oxidative processes during meat storage. This strategy enhances the preservation of key nutrients (proteins, vitamins, and PUFAs), facilitates the formation of meat with superior sensory and dietary properties, and broadens the application of natural phytocomponents as alternatives to synthetic antioxidants in the production and preservation of waterfowl meat.

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CHAPTER 8

Reducing losses during storage of fruit vegetables: regulation of postharvest metabolism

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Abstract

This review article addresses modern strategies for reducing postharvest losses in fruit vegetables by regulating oxidative metabolism during storage. Fruit vegetables such as tomatoes, peppers, eggplants, cucumbers, zucchinis, pumpkins, and melons are highly perishable and susceptible to chilling injury due to their intense postharvest respiration and high moisture content. The article summarizes the physiological and biochemical responses of plant tissues to cold stress, including membrane damage, oxidative stress, and the imbalance of endogenous antioxidants. Emphasis is placed on combined treatment approaches that integrate physical methods (heat treatments, UV irradiation, modified atmosphere storage) with the application of bioactive substances, including phytohormones and natural antioxidants. The review highlights the role of heat-induced stress tolerance, antioxidant defense systems, and nanostructured delivery forms in mitigating cold-related metabolic disorders. It argues that the effectiveness of such strategies depends on species- and cultivar-specific responses, maturity stage, and preharvest conditions. A physiological understanding of tissue metabolism is essential to optimize storage parameters and design effective protective treatments.

Keywords

Fruit vegetables, postharvest metabolism, oxidative stress, chilling injury, antioxidants, bioactive substances, heat treatment, storage technologies, combined treatments.

8.1 Introduction

Fruit vegetables are one of the most popular and valuable groups of vegetable crops, including tomatoes, peppers, eggplants, cucumbers, zucchinis, pumpkins,

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and other fruit-forming plants. They are an essential component of a healthy diet. In 2023, global vegetable production reached 1.2 billion tons, which is 26% higher compared to 2010. Fruit vegetables have high economic profitability and are provided fresh and canned, or as ingredients for food concentrates. Among all fruit vegetables, the highest production volume is attributed to tomatoes (*Solanum lycopersicum*) [1]. Other leading crops include sweet peppers (*Capsicum annuum*), cucumbers (*Cucumis sativus*), and zucchinis (*Cucurbita pepo*), which form the basis for both fresh consumption and processed products.

Fruit vegetables contain sugars, organic acids, polysaccharides, proteins, and lipids, with the percentage ratio of these components depending on breeding and genetic characteristics, as well as biotic and abiotic factors. The value of fruit vegetables lies in their content of bioactive compounds – natural endogenous antioxidants, minerals, dietary fibers, and other phytonutrients capable of addressing the issue of "hidden hunger". In the context of the global transformation of food systems, there is a shift in nutritional approaches with an emphasis on increasing the share of vegetables in the daily diet. This is driven not only by the need for healthier eating but also by the necessity to reduce the carbon footprint associated with the consumption of animal-based products.

However, fruit vegetables are highly sensitive to external factors, exhibit intense postharvest metabolism, and have a short shelf life, which leads to significant losses at all stages of the food supply chain – from harvest to consumption. According to the Food and Agriculture Organization of the United Nations (FAO), fruits and vegetables have the highest loss rate among all food categories – ranging from 40% to 50% of their total volume [2]. These losses have serious economic and environmental consequences, as vegetable production requires substantial natural resource inputs, including water, soil, fertilizers, and energy. Moreover, the loss of such valuable raw materials during storage contradicts the principles of sustainable development, creates additional environmental burdens, and undermines food security.

Ensuring the availability and quality of vegetable products requires comprehensive solutions, including infrastructure modernization, expansion of technological capabilities, the implementation of innovative approaches such as automated systems for monitoring product conditions, alternative methods for extending shelf life, and the adaptation of global experience in the agri-industrial sector [3]. Only an integrated approach will reduce vegetable losses and contribute to the development of sustainable food systems.

Modern storage technologies are based on slowing down postharvest metabolism and maintaining the antioxidant defense system of the fruit [4]. Therefore, the aim of this study was to discuss the mechanisms and strategies for regulating postharvest metabolism, as well as technologies aimed at minimizing oxidative stress, which affects the quality and shelf life of fruit vegetables.

8.2 Biochemical processes in postharvest metabolism

After harvesting, fruit vegetables continue their life cycle, maintaining active metabolism. However, the supply of assimilates, water, and phytohormones from the parent plant ceases, so they rely on previously stored organic compounds. The primary metabolic processes include respiration, ethylene production, and oxidative reactions, which directly affect quality, shelf life, and resistance to stress factors. Respiration is a key process during which organic substances (mainly acids and sugars) are oxidized to produce energy necessary for maintaining cellular activity. After harvesting, the intensity of respiration often increases, leading to faster depletion of nutrient reserves, weight loss, and accelerated aging of the produce. This is particularly characteristic of vegetables with high moisture content and thin skin, such as tomatoes, cucumbers, peppers, and eggplants. Some fruit vegetables (e.g., tomatoes and eggplants) are climacteric, meaning they exhibit a sharp (climacteric) spike in respiratory activity, intense ethylene synthesis, and the ability to ripen postharvest. Ethylene is a phytohormone that activates respiration and regulates ripening and aging processes. During the storage of tomatoes under cooling conditions, respiratory intensity is initially inhibited due to the low temperature. However, after approximately five days of storage, respiratory intensity increases. Subsequently (around 20 days), a climacteric rise occurs, followed by a decline in respiratory activity, during which overripening processes dominate, as indicated by the deterioration of fruit quality [5].

The level of CO_2 emission and the timing of the climacteric phase vary depending on the variety or hybrid of tomatoes and the abiotic factors during cultivation. The climacteric phase is accompanied by physiological changes such as tissue softening, color changes, and aroma development, which make the fruits more appealing for consumption. However, after the onset of the climacteric phase, the fruits quickly lose their properties and degrade. Therefore, delaying the onset of the climacteric phase as much as possible extends the overall storage period.

Non-climacteric fruit vegetables (e.g., peppers, cucumbers, zucchinis) do not exhibit a sharp spike in respiratory activity and are characterized by low levels of endogenous ethylene. In non-climacteric vegetables, ethylene interacts with other phytohormones, such as abscisic acid (ABA) and auxins, which influence ripening and aging processes. These interactions can modulate tissue sensitivity to ethylene and affect product quality during storage. It has been established that the postharvest respiration rate of non-climacteric fruit vegetables is closely correlated with weather conditions during the preharvest period [5, 6]. Non-climacteric vegetables do not have the ability to ripen postharvest and gradually degrade during storage. Lowering the storage temperature slows down metabolic processes accordingly.

During storage, reactive oxygen species (ROS) accumulate in the cells of fruit vegetables, which can damage membranes, proteins, and nucleic acids. This phenomenon is known as oxidative stress. To neutralize ROS, plants utilize endogenous antioxidant systems, which include enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), as well as low-molecular-weight compounds like ascorbic acid (AA), glutathione, phenolic compounds, and carotenoids [4]. The enzymatic and non-enzymatic antioxidant systems work together to neutralize reactive oxygen species, thereby preserving the quality of the fruits. Their activity depends on the type of vegetable, the variety, and the storage conditions. For example, tomatoes are rich in lycopene and ascorbic acid, pumpkins are abundant in β-carotene and phenolic compounds, while peppers contain high levels of ascorbic acid and peroxidase (**Table 8.1**).

Table 8.1 Fruit vegetables and components of antioxidant defense

Fruit vegetable species	Key antioxidant compounds and enzymes	Postharvest action features
Tomato (*Solanum lycopersicum*)	Lycopene, AA, SOD, POD, polyphenols, flavonoids	Reduction of AA content by up to 50%. SOD is activated in response to mechanical damage or over-ripening of the fruit
Sweet pepper (*Capsicum annuum*)	Ascorbic acid, Carotenoids (capsanthin, capsorubin), SOD, CAT, phenolic compounds	Reduction of AA during storage; increase in POD and SOD activity under chilling
Eggplant (*Solanum melongena*)	Chlorogenic acid, anthocyanins, POD, CAT	High phenolic content, which increases under mechanical stress
Zucchini (*Cucurbita pepo*)	Ascorbic acid, polyphenols, SOD, CAT, flavonoids	Activation of phenolics and increase in antioxidant activity under low temperature conditions
Cucumber (*Cucumis sativus*)	Ascorbic acid, POD, flavonoids	Reduction of AA during storage; activation of flavonoid synthesis in response to chilling and mechanical stress
Pumpkin (*Cucurbita maxima*, *C. moschata*)	Carotenoids (β-carotene, lutein), SOD, CAT, polyphenols	Moderate reduction in AA and carotenoid content during storage, SOD activity increases in response to storage-related oxidative stress
Watermelon (*Citrullus lanatus*)	Lycopene, ascorbic acid, β-carotene, SOD, CAT, phenolic compounds,	Reduction of AA and lycopene during storage. SOD, CAT activity decrease as senescence progresses
Melon (*Cucumis melo)*	Ascorbic acid, carotenoids (β-carotene), phenolic acids, flavonoids, SOD, CAT	Gradual decline in ascorbic acid and carotenoid content during storage; antioxidant enzyme activities (e.g., SOD, CAT) decrease with senescence

Source: compiled from data [7–12]

Fluctuations or reductions in temperature and humidity, changes in storage atmosphere, and postharvest treatments can either activate or suppress the antioxidant defense systems of fruit vegetables. When the production of substances necessary to maintain normal cellular homeostasis is disrupted, the cell's ability to counteract reactive oxygen species (ROS) is only effective for a limited time. As the cell ages, these compounds begin to accumulate, and the defense system becomes depleted. This leads to metabolic disturbances and, ultimately, cell death.

The biochemical processes occurring in vegetables during storage are closely linked not only to physiological processes (e.g., respiration) but also to physical processes, such as moisture transpiration. After harvest, fruit vegetables continue to lose moisture through transpiration, which results in reduced cell turgor, wilting, and surface wrinkling. Dehydration leads to a decline in enzyme activity, inhibition of respiration, protein synthesis, and other metabolic processes. This is a protective response of the organism, allowing it to preserve cellular structure under unfavorable conditions. On the other hand, moisture loss stress can activate certain enzymes, such as those associated with aging or tissue oxidation.

Moisture loss is the second most significant cause of deterioration during storage, following overripening, particularly in physiologically immature vegetables such as cucumbers, zucchinis, and eggplants. Moisture loss negatively affects the appearance and consumer properties of the vegetable production. The rate of moisture loss depends on storage conditions, particularly temperature and relative humidity. Lowering the storage temperature significantly slows transpiration, which is a critical factor in maintaining the commercial appearance and weight of the product.

However, while reducing temperature is beneficial for limiting transpiration and suppressing metabolism, it also poses a risk of cold-induced damage, especially for vegetables of tropical and subtropical origin. Such temperature reductions can lead to the development of a complex of metabolic disorders that degrade the quality.

8.3 Metabolic disorders induced by cold exposure

For fruit and vegetable products of tropical and subtropical origin, cold storage often leads to the development of a complex of metabolic disorders that negatively affect quality. This set of changes is collectively known as chilling injury (CI). Fruits sensitive to CI typically have a short storage life because low temperatures, which are effective in delaying aging and suppressing the development of pathogenic microorganisms, cannot be used for their preservation. The storage life of chilling-sensitive produce increases as the storage temperature decreases, but only to a certain

threshold, referred to as the critical chilling temperature. For subtropical plant species, this critical temperature is approximately 8°C, while for tropical species, it is around 12°C. The approximate critical temperatures at which signs of chilling injury begin to appear in fruit vegetables are provided in **Table 8.2**.

Table 8.2 Chilling sensitivity of fruit vegetables

Crop		Chilling injury threshold, °C	Estimated time to onset of chilling injury symptoms, days
Cucumber		≤ 10	2–3
Zucchini		≤ 5	2–3
Melon		≤ 7	4–7
Watermelon		≤ 10	5–10
Pumpkin		≤ 10	14–28
Sweet pepper		≤ 7	4–10
Eggplant		≤ 10	2–5
Tomato	Green mature	≤ 13	4–7
	Breaker	≤ 13	3–5
	Pink-light red	≤ 10	7–10
	Red ripe	≤ 7	10–14

Source: compiled from data [13–15]

Sensitivity to CI strongly depends on the duration of exposure to suboptimal temperatures, the variety, growing conditions, the developmental stage of the fruit, and the storage environment.

The symptoms of chilling injury vary depending on the type of produce. Some common symptoms for tropical plants include the appearance of lesions, discoloration, sliminess, internal breakdown, inability to ripen, loss of taste and aroma, and decay. Spots, round or irregularly shaped depressions on the fruit surface, as well as uneven coloration, are the most common forms of chilling damage and the first symptoms observed in many vegetables (including cucumbers, zucchinis, sweet peppers, and tomatoes) (**Fig. 8.1**).

At the microscopic level, the symptoms of chilling injury are similar across all plant organisms. These symptoms include swelling and disorganization of mitochondria and chloroplasts, where thylakoid expansion and granum disassembly occur, a reduction in the size and number of starch granules, accumulation of lipid droplets inside mitochondria, and condensation of nuclear chromatin [15]. The first physiological response to low-temperature exposure is changes in the conformation and structure of the cell membrane. Due to reduced solubility and depolymerization of pectin, the

permeability of cell walls changes significantly. The most critical changes occur in the lipid composition of membranes, which are similar to those observed during aging. These changes include lipid peroxidation, an increase in the saturation index of fatty acids, degradation of phospholipids and galactolipids, and an increased sterol-to-phospholipid ratio. If the storage period at low temperatures is excessively long, the cell membrane loses elasticity, ruptures, and water, ions, and cellular metabolites leak out. As a result, a cascade of secondary reactions occurs, such as loss of turgor, electrolyte leakage, loss of metabolic energy, disintegration of photosynthetic systems, and ultimately, cell lysis. Prolonged exposure to low temperatures makes it impossible to restore the original cellular organization upon warming. Moreover, the symptoms of CI become more pronounced when vegetables are transferred to room temperature.

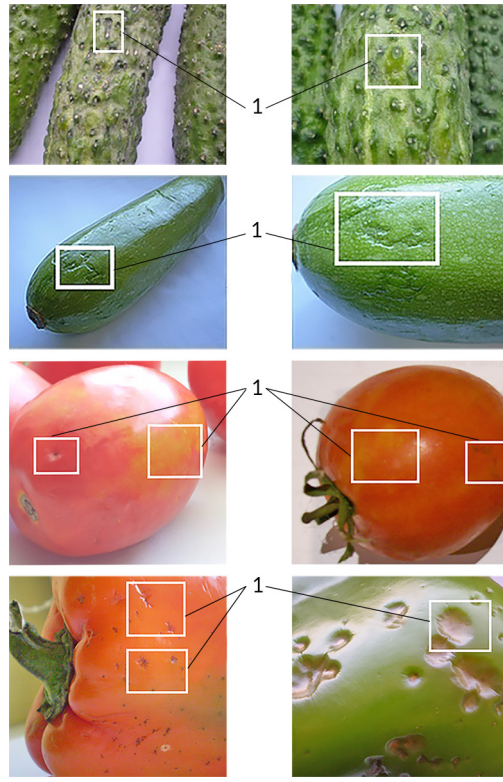

Fig. 8.1 Symptoms of chilling injury in various vegetables: 1 – area showing chilling injury
Source: author's photo

In addition to the direct impact of low temperatures on the molecular organization of membrane lipids, membrane integrity is further compromised by oxidation. Low-temperature stress is accompanied by the generation of high levels of reactive oxygen species (ROS). Excessive ROS production occurs in chloroplasts, which are involved in photosynthesis and have an oxygen surplus. Another source of ROS is the activation of NADPH oxidases localized in cell membranes, which leads to massive production of superoxide anions. This also results in lipid peroxidation of membranes. Oxidative stress is exacerbated by the inhibition of antioxidant enzyme activity, which is responsible for ROS removal. Overall, researchers agree that oxidative stress plays a leading role in the induction of chilling injury.

8.4 Physical methods for regulating postharvest metabolism

Various postharvest technologies are available to delay the development of chilling injury during the storage of sensitive produce. Some of these technologies are physical in nature and primarily involve modifying temperature, relative humidity, or the gas composition of the storage atmosphere for fruits and vegetables. However, controlled atmosphere storage, depending on the type of produce, can be beneficial, ineffective, or even harmful in reducing chilling injury. For example, controlled atmosphere storage has advantages for zucchinis, does not affect tomatoes, and exacerbates chilling symptoms in cucumbers and sweet peppers [14]. It is known that the use of modified atmosphere storage can effectively reduce chilling injury symptoms in tomatoes and zucchinis, especially when the correct combination of temperature, oxygen concentration, and fruit maturity stage is applied. Pre-treatment with 10% CO_2 for 24 hours, combined with a modified atmosphere, reduces CI symptoms in sweet peppers, including calyx darkening and loss of firmness [16]. However, considering the principles of sustainable production, the use of film materials for creating a modified atmosphere raises significant concerns regarding their application.

Some studies suggest that ultraviolet (UV) irradiation of fruits can reduce chilling sensitivity by stimulating defense mechanisms, including increased activity of antioxidant enzymes. UV treatment induces the formation of phenolic compounds and flavonoids, which help combat oxidative stress and may extend shelf life by strengthening cellular structures and enhancing immune responses. It is known that UV irradiation increases the chilling resistance of tomatoes. Recent studies have shown that UV irradiation of zucchinis enhances their resistance to chilling by increasing flavonoid accumulation and antioxidant capacity, thereby reducing oxidative stress during low-temperature storage [17].

At the industrial level, the most commonly used methods include conditioning at moderate temperatures, pre-storage heat treatments at high temperatures, or interrupting cold storage with temporary warming of the produce (either once or periodically). This approach aligns with the requirements of the European Green Deal. The positive effects of heat treatments are associated with the formation and protective action of heat shock proteins (HSPs). HSPs play a role in regulating ROS production and protecting cellular compartments from oxidative stress. Heat-induced thermotolerance can also provide protection against cold stress. Postharvest heat treatments alter the normal protein synthesis program and cellular metabolism. Under heat stress, rapid dissociation of polyribosomes occurs, and protein synthesis temporarily halts. It then resumes with a new set of proteins, including HSPs. As a result, normal ripening processes are blocked, and if the product is stored at low temperatures, this inhibition persists for some time. Thus, postharvest heat treatments can not only delay the development of chilling injury, but also modulate the rate of ripening and aging of the produce [18].

Heat conditioning procedures are typically carried out in hot air at temperatures ranging from 30°C to 40°C, with durations ranging from a few hours to several days. Higher temperatures are used for insecticidal and fungicidal purposes. In industrial settings, the most common methods include hot water dipping (HWD) and hot water rinsing and brushing (HWRB) or spraying [19]. Heat treatment also directly reduces the number of pathogenic microorganisms by destroying or inactivating spores. The temperature and duration of exposure can vary significantly (from 33°C for several days to 63°C for a few seconds) and are typically determined experimentally for specific plants and purposes (**Table 8.3**).

Table 8.3 Postharvest heat treatment regimens for fruit vegetables

Treatment method	Temperature, °C	Duration	Target application	Crops
1	2	3	4	5
Hot air (conditioning)	35–39	12–72 h	Reduction of chilling injury symptoms, delay of ripening	Tomato, Eggplant, Pepper
HWD	42–50	3–10 min	Reduction of chilling injury symptoms, control of fungal pathogens	Eggplant, Pepper, Cucumber
	45	15 min	Reduction of chilling injury symptoms	Tomato
	55	1 min	Prolonged storage life, reduced fusarium disease and fruit decay, improved fruit quality	Melon

Continuation of Table 8.3

1	2	3	4	5
HWRB	59°C	15 s	Control of fungal pathogens, improved fruit quality	Melon
	54°C	15 s	Control of fungal pathogens, improved fruit quality	Pumpkin
	55°C	12 s	Maintaining fruit quality after prolonged storage	Pepper
	52°C	15 s	Enhancing cold tolerance, maintaining quality during storage	Red tomato
Steam treatment	50–55°C	5–15 min	Reducing water loss, controlling pathogens	Tomato, Pepper
Combined conditioning + cooling	38°C → 12°C	24 h + storage	Enhancing cold tolerance, maintaining quality during storage	Tomato, Eggplant

Source: compiled from data [6, 12, 13, 18–22]

Fruits and vegetables with green coloration may experience yellowing when exposed to high temperatures. This phenomenon is explained by the activation of chlorophyllase, which leads to chlorophyll degradation. Therefore, for cucumbers and zucchinis, heat treatments at temperatures not exceeding 45°C are recommended.

Overall, the effects of heat treatments on fruits and vegetables mitigate cold stress through the following factors [13]:

– enhancing membrane integrity by increasing the ratio of unsaturated fatty acids to saturated fatty acids;

– increasing the expression of heat shock protein (HSP) genes and their accumulation;

– boosting the antioxidant activity of the system;

– enhancing arginine synthesis pathways, leading to the accumulation of signaling molecules (polyamines, nitric oxide, and proline) responsible for improving cold tolerance;

– altering the activity of phenylalanine ammonia-lyase and polyphenol oxidase enzymes;

– enhancing carbohydrate metabolism.

8.5 Regulation of postharvest metabolism using biologically active substances

One of the effective approaches to controlling metabolism and enhancing cold tolerance is the use of biologically active substances (BAS), which can modulate the

physiological state of vegetable, reduce metabolic intensity, stabilize cellular structures, and strengthen antioxidant defenses.

Bioregulation through phytohormones. Phytohormones (such as auxins, gibberellins, cytokinins, abscisic acid, ethylene, and others) are natural substances produced by plants that regulate their growth, development, and responses to stress factors. Researchers studied the synthetic first-generation cytokinin, 6-benzylaminopurine (6-BA), also known as benzyl adenine or BA, as a postharvest treatment for cucumbers to mitigate chilling injury [23]. They found that exogenous 6-BA allows fruits to maintain higher levels of chlorophyll, ascorbic acid, phenolic compounds, and overall antioxidant capacity. Additionally, this treatment increases the activity of superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APX), and glutathione reductase (GR) under cold stress. The results demonstrate that 6-BA alleviates CI symptoms in cucumbers by enhancing the activity of antioxidant enzymes and overall antioxidant activity.

Cytokinins have also been shown to reduce cold sensitivity in zucchini [17]. To mitigate chilling symptoms, treatments with phytohormones such as methyl jasmonate and methyl salicylate have been proposed. Methyl jasmonate reduces CI in zucchini [17], however is ineffective in reducing CI symptoms in peppers [24]. Other phytohormones, such as salicylic acid, melatonin, and brassinosteroids, demonstrate the ability to strengthen the fruit's antioxidant system, increasing the activity of SOD, CAT, and polyphenol oxidase (POD), which aids in adaptation to low temperatures and limits the development of CI.

Postharvest metabolism can also be regulated by influencing the phytohormones of fruits. Retardants and ethylene inhibitors are widely used to control ripening and aging processes. For example, 1-methylcyclopropene (1-MCP), an ethylene receptor inhibitor, effectively reduces tissue sensitivity to ethylene, delays fruit softening, slows chlorophyll loss, and extends the shelf life of vegetables, including zucchinis, tomatoes, and eggplants. However, it does not affect chilling injury in peppers [24]. It is likely that the use of 1-MCP only alleviates CI symptoms and requires additional protective measures against low temperatures. When plants are treated with growth regulators that induce cold tolerance, the fruits generally become less sensitive to chilling during storage. The use of phytohormones stimulates the production of endogenous antioxidants. However, the antioxidant defense of tissues can also be supplemented by using exogenous BAS with antioxidant properties.

Antioxidant protection and regulation of oxidative stress. Treatment of fruits and vegetables with compounds that act as antioxidants and reduce oxidative damage induced by chilling is widely applied during the storage of vegetables. The advantage of synthetic antioxidants over natural ones lies in their higher free radical

scavenging activity, greater stability, slower degradation by cellular monooxygenase systems, and prolonged action. Numerous synthetic compounds, including butylated hydroxytoluene (BHT), ethoxyquin, and diphenylamine, have been recognized as highly effective in preventing oxidative browning in various fruits and vegetables. However, concerns about the environmental impact of chemical compounds have driven increased attention toward natural antioxidants.

Natural antioxidants have become an alternative to synthetic ones because they are fully biodegradable and environmentally safe. However, natural exogenous compounds are not as universally effective as synthetic ones, meaning they may only be beneficial for specific vegetables. Additionally, for antioxidant components to be effective, they must easily reach the target site of oxidative damage, which is typically achieved by lipophilic compounds. Extensive research has been conducted on treating fruits and vegetables with ascorbic acid, tocopherol, glutathione, polyphenolic compounds (quercetin, resveratrol, rutin), and chitosan. Single-component antioxidants are generally less effective than compositions containing two or more antioxidants [21]. Each year, hundreds of studies are published on the antimicrobial and other functional properties of extracts from higher plants. The use of higher plants and their components as antioxidants, bactericides, or fungicides provides such advantages as better systemic action, non-phytotoxicity, and biodegradability. These compounds can be applied continuously year after year without any negative impact on the environment. A wide range of available spices and herbs exhibit fungicidal, bactericidal, and antioxidant properties, including marjoram, cumin, savory, basil, coriander, mustard, and horseradish. Understanding their characteristics and specific mechanisms of action will help evaluate their contribution to regulating the metabolic processes in fruit tissues. It has been demonstrated that such treatments reduce the intensity of lipid peroxidation in cellular membranes [12]. This, in turn, decreases cellular damage, delays turgor loss, and prevents premature tissue breakdown.

Modern approaches involve the use of bioactive compounds in the form of nanomaterials, encapsulation in polymer carriers, or incorporation into active packaging films. For example, applying edible coatings with the addition of horseradish extracts and lecithin as an antioxidant delays the development of chilling injury in tomatoes by 2 weeks during storage at 2°C [21].

Treatment with bioactive substances is a promising approach for extending the storage life of fruit vegetables, reducing chilling injury, and maintaining nutritional value. The combination of phytohormonal regulators, antioxidants, and protective natural compounds effectively regulates postharvest metabolism. However, optimal concentrations, application methods, and combinations of bioactive substances must be tailored to specific vegetable types and storage conditions.

8.6 Combined methods for protecting fruit vegetables from oxidative damage

Numerous approaches proposed to reduce chilling injury do not completely prevent the appearance of chilling symptoms in most vegetables. However, oxidative stress-induced damage can be mitigated by combining different measures. Various external stressors trigger similar mechanisms to enhance resistance to oxidative stress. This explains why many different postharvest treatments can reduce physiological disorders induced by oxidative stress. When two or more stressors are applied simultaneously, plant tissues develop broader stress cross-tolerance [25].

It has been established that combining heat treatment with antioxidant application reduces the severity of chilling injury in red tomatoes [21]. The low-temperature damage index in treated fruits, depending on the tomato variety and antioxidants used, was 7.0–14.7 times lower compared to untreated fruits and 3.3–7.7 times lower than in tomatoes treated with hot water alone. Similar results were obtained when combining heat treatment with antioxidant solutions for two varieties of peppers. Pre-storage treatment with a solution of a complex natural-synthetic antioxidant at 45°C for 15 minutes extended the storage life of peppers by 2 weeks. This postharvest treatment reduced the sensitivity of peppers to low-temperature storage: the level of chilling damage decreased by 7–9 times, and the severity of low-temperature injuries in treated fruits was reduced by 9–12 times. Heat treatment combined with antioxidants significantly affects the level of lipid peroxidation products during zucchini storage [12]. This treatment stabilizes the level of malondialdehyde throughout the storage period, indicating the full activation of antioxidant defense mechanisms and timely utilization of ROS.

Despite researchers' efforts, no universal solution has been found to prevent metabolic disorders during the storage of fruit vegetables. Slowing tissue oxidation can be achieved by combining antioxidants with heat treatment. However, strategies for combined protection measures must be developed with a clear understanding of the biochemical responses of tissues. Species and varietal specificity, developmental stage, and growing conditions significantly influence tissue responses to storage-induced stress factors. For example, the ability to activate the endogenous antioxidant system or the effectiveness of exogenous biologically active substances varies not only between crops but also among varieties within the same species.

The successful implementation of combined technologies is possible only with the targeted selection of physiologically justified parameters, such as temperature and duration of heat treatment, antioxidant concentration, and the sequence and method of application (e.g., spraying, dipping, or vapor treatment). Additionally,

potential negative effects of excessive metabolic inhibition, such as delayed ripening or loss of flavor, must be considered. Thus, a promising direction is the integration of physiological monitoring (e.g., malondialdehyde content, antioxidant enzyme activity) with practical storage technologies. Such approach allows the adaptation of protection systems to the specific properties of each batch of vegetable produce, ensuring optimal storage outcomes.

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CHAPTER 9

Essential oils in pig diet as a means of improving pork quality

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Abstract

The conducted study of the influence of the feed additive "Activo" on the physicochemical properties and fatty acid composition of the liver and meat of pigs allowed to detect significant changes in lipid metabolism, which contributes to the improvement of the quality characteristics of the meat. In the meat of pigs of the experimental group, a significantly lower content of peroxide oxidation products was found. Analysis of the fatty acid composition of the liver of pigs proved that the use of the feed additive contributed to a change in the profile of saturated, monounsaturated and polyunsaturated fatty acids. In the meat of pigs of the experimental group, a decrease in the level of stearic and pentadecanoic acids was found, while an increase in the level of monounsaturated fatty acids, in particular oleic acid, was recorded, which contributes to positive changes in the organoleptic characteristics of the meat.

The results obtained allow to conclude that the addition of the feed additive "Activo" affects lipid metabolism in pigs, changing the balance of fatty acids in the liver and muscles, and also contributes to the inhibition of oxidative damage to the lipid component of meat. The detected changes positively affect the quality of meat, in particular its antioxidant status, heat resistance and organoleptic properties.

Keywords

Pork, feed additive, fatty acid composition, essential fatty acids, ω-3 and ω-6 fatty acids, oxidative spoilage, organoleptic properties.

9.1 Introduction

Modern husbandry is in the process of active transformation, aimed at finding safe and effective alternatives to antibiotics. The traditional use of feed antibiotics

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for pigs ensured high productivity, but at the same time it accumulates of excess substances in animal products and increased antibiotic resistance of microorganisms [1]. The development of natural additives that can replace antibiotics without negative consequences for the health of animals and people is becoming one of the priorities for the modern feed industry.

One of the promising alternatives is the use of ethereal oils, which have a wide range of biological effects, including anti-inflammatory, antioxidant and antimicrobial activity [2–4]. Essential oils contain natural terpenoid compounds, which have a positive effect on physiological processes in the human body. They are obtained by steam distillation or extraction by distillers and are used as biologically active components for to improve feed absorption, stimulating digestion and maintaining an optimal balance of intestinal microflora [5, 6]. Recent studies have shown that essential oils can modulate lipid metabolism by influencing the synthesis and oxidation of fatty acids in the liver and muscle. This, in turn, is reflected in the fatty acid profile of meat, improving its quality and sensory characteristics [7]. The influence of essential oils on lipid metabolism is an important aspect for the production of meat products with improved fatty acid composition, which meets the growing consumer demands for healthy and safe nutrition [8].

In addition, essential oils can affect the structural features of muscle tissue, muscle fiber types, and collagen structures that determine the tenderness and texture of meat [9, 10]. Skeletal muscle tissue contains fibers of different types, classified by metabolic activity and contractile properties. It is the ratio of muscle fiber types and their morphological characteristics that affect the final meat quality indicators, including tenderness, juiciness, and water-holding capacity [11]. Research of the mechanisms of the influence of essential oils on muscle morphology is an important direction of modern science, contributing to increasing the efficiency of meat production.

One of such effective feed additives is "Activo", a combination of biologically active compounds obtained from aromatic herbs and spices. It includes essential oils of cinnamon, rosemary, oregano, and chili pepper extract. According to numerous studies, these components have pronounced antioxidant, anti-inflammatory, hepatoprotective properties, stimulate the activity of digestive enzymes, improve feed conversion, and also have a bactericidal effect, inhibiting the development of pathogenic microflora. The positive effect of a feed additive containing biologically active essential oils and extracts on the processes of synthesis of structural lipids, and especially the synthesis of phospholipids in the muscle tissue of pigs has been proven [12]. Studies by S. Huang et al. [13] have proven that the addition of 200 mg/kg of essential oils to the diet of pigs significantly increases the average daily body weight gain

and improves nutrient absorption. An increase in antioxidant activity in the muscles and liver was also noted, which was manifested in a decrease in the level of the lipid oxidation marker malondialdehyde. Studies by S. Chen et al. [14] demonstrated that dietary supplementation with oregano essential oil (OEO) and benzoic acid (BA) improved the stability of fatty acids in muscle tissue and reduced moisture loss in meat. A decrease in linoleic acid and an increase in oleic acid were observed, which positively affected the organoleptic properties of meat.

According to the results of the studies by K. Czyż et al. [15], essential oils are able to change the fatty acid profile in the skeletal muscles of pigs, reduce the proportion of saturated fatty acids (SFA) and increase the content of polyunsaturated fatty acids, in particular omega-3. This aspect is of great importance for consumers, since meat with an increased content of omega-3 fatty acids has improved nutritional properties and contributes to human health. Studies by A. B. Smith et al. [16] also confirm that the use of essential oils in pig feeding promotes the activation of genes responsible for lipid metabolism, such as LPL (lipoprotein lipase), CD36 (fatty acid transporter) and CPT-1 (carnitine palmitoyltransferase-1), which indicates the stimulation of the processes of β-oxidation of fatty acids.

However, the published results of the research by M. V. Valero et al. [17] reported that the addition of essential oils does not have a significant effect on the overall composition of fatty acids in meat. Thus, when propolis and essential oils were added to the diet of fattening bulls, no significant changes in the composition of fatty acids in the long chest muscle were recorded. At the same time, according to V. Vasta and R. Bessa [18], some essential oils can modulate the processes of rumen biohydrogenation and affect the composition of fatty acids in the muscles, although the mechanism of this effect requires further research.

Under the influence of the feed additive "Activo", there was a significant decrease in the content of unesterified cholesterol in the latissimus dorsi muscle ($p \leq 0.001$) and an increase in the content of phospholipids ($p \leq 0.001$) [18]. The effect of the feed additive "Activo" on the content of lipid peroxidation products and the activity of antioxidant enzymes in sows and piglets obtained from them was also studied. It was found that the use of the feed additive "Activo" for sows and piglets obtained from them helps to reduce the negative impact of oxidative stress, which negatively affects both sows and their offspring. This led to an improvement in slaughter yield by 6.59% in the experimental group [12]. Feeding rearing pigs of "Activo" has no probable effect on the change of physico-chemical indicators of meat quality. However, the actual figures have some differences in individual indicators within the statistical deviations. Laboratory studies of the Longissimus dorsi muscle showed that there was no significant difference between trial and control groups in water holding

capacity of muscle tissue. Also, there is no significant difference in terms of meat marbling and color intensity.

Thus, the previously published results confirm the effectiveness of the feed additive "Activo" for improving the general condition of animals, increasing the digestibility of nutrients and improving the quality characteristics of meat. The effect of essential oils on antioxidant status and lipid metabolism is an important factor in reducing the level of oxidative processes, which contributes to extending the shelf life of meat products. However, further studies are needed to more fully determine the mechanisms of action of essential oils, including the analysis of their effects on morphological changes in muscle tissue and the dynamics of biochemical processes in the liver and skeletal muscles of pigs [19].

The aim of this work was to determine the effect of the phytogenic feed additive "Activo" on the fatty acid composition of the liver and muscle tissue of pigs. The results obtained will allow to draw a conclusion about the feasibility of using essential oils as a functional component of feed to increase animal productivity and improve the quality characteristics of meat.

9.2 Schemes and methods of research

The study was conducted at a pig farm located in the Odesa region. The experiment used piglets of the same age with an average body weight of 70 kg, which were divided into two groups according to the principle of analogues: control and experimental, 43 animals in each group. The pigs were kept in standard conditions within the same premises with the same microclimate parameters and technological regime. Feeding was carried out with standard compound feed (CF), balanced in terms of essential nutrients, vitamins and trace elements. The composition of the compound feed included: wheat, barley, corn, soybean meal, full-fat soybean, sunflower meal, NutriMix 70–115 kg premix (3.0%), recipe: 380673222001-C5 Nutrimin Finish 70–115 kg.

After a preparatory period lasting one month, the phytogenic feed additive "Activo" was introduced into the diet of the pigs of the experimental group in the amount of 0.1 kg/t of compound feed. The duration of the experiment was 40 days.

Phytogenic supplement "Activo" contains a combination of biologically active substances of plant origin that affect the metabolic processes of the pig's body. The components of the supplement include: cinnamon essential oil, which stimulates taste and olfactory receptors, has anti-inflammatory properties, reduces stress levels and exhibits antioxidant activity; rosemary essential oil, which acts as a natural antioxidant

and anti-inflammatory agent, regulates the body's thermoregulation, reduces oxidative stress and pain during inflammatory processes; chili pepper extract, which helps increase appetite, stimulates salivation, activates the secretion of gastric juices and enzymatic activity, which has a positive effect on the absorption of nutrients and increases feed conversion; oregano essential oil, which has a pronounced bactericidal activity, inhibits the development of gram-positive and gram-negative bacteria, as well as viruses and fungal microorganisms. This component has a positive effect on the functioning of the digestive system and the antioxidant status of the body.

At the end of the study animals of both groups were control-slaughtered and samples of liver, longissimus dorsi and latissimus dorsi muscles were taken for laboratory studies. The study is fully complied with the ethical requirements for the use of animals in experimental research (Strasbourg, 1986; Kyiv, 2002), and the research methodology was approved by the Bioethics Committee of the Institute of Animal Biology of the National Academy of Agricultural Sciences of Ukraine (Protocol No. 93-01 from 03.06.2021).

The determination of the fatty acid composition of lipids was performed by gas chromatography [20] on an Agilent Technologies 7890A gas chromatograph using a ZB-FAME capillary column (length 60 m, internal diameter 0.25 mm, phase thickness 0.20 μm; carrier gas: helium; carrier gas flow rate: 1.2 ml/min; detector temperature (DTC): 280°C; injector temperature: 250°C). The Student's *t*-test and Microsoft Excel software was used for the statistical calculation of digital data.

9.3 Results and discussion

9.3.1 Analysis of the fatty acid composition of the liver of pigs

Analysis of the fatty acid composition of the liver of pigs fed the feed additive "Activo" demonstrates significant changes in the profile of saturated (SFA), monounsaturated (MUFA) and polyunsaturated (PUFA) fatty acids compared to the control group (**Table 9.1**).

In the experimental group receiving the feed additive, a decrease in the concentration of some SFA was recorded. In particular, the content of lauric acid in the liver of pigs in the experimental group decreased by 1.60 times ($p < 0.05$) compared to this indicator in animals in the control group, and the content of pentadecanoic acid decreased by 1.45 times ($p < 0.001$), respectively. At the same time, there was an increase in the level of palmitic acid, its share increased by 17.9% ($p < 0.01$), which indicates a possible effect of the additive on the processes of lipogenesis in the liver.

Table 9.1 Fatty acid composition of the liver fed with the additive "Activo" ($M \pm m$, $n = 5$)

Fatty acid	Code	Groups	
		Control	Experiment
Lauric	12:0	0.08 ± 0.009	0.05 ± 0.003*
Myristic	14:0	0.22 ± 0.017	0.292 ± 0.023*
Pentadecanoic	15:0	0.24 ± 0.005	0.166 ± 0.009***
Palmitic	16:0	13.34 ± 0.226	15.728 ± 0.611**
Palmitoleic	16:1	0.30 ± 0.004	0.596 ± 0.049***
Margarine	17:0	2.160 ± 0.027	1.382 ± 0.103***
Heptadecenoic	17:1	0.244 ± 0.022	0.270 ± 0.031
Stearic	18:0	30.188 ± 0.289	27.002 ± 1.223*
Oleic	t 18:1	0.512 ± 0.009	0.374 ± 0.036**
	c9 18:1	8.190 ± 0.118	13.124 ± 0.525***
	c11 18:1	1.238 ± 0.014	1.328 ± 0.039
Linoleic	c, t 18:2	0.220 ± 0.004	0.186 ± 0.014
	18:2 ωn6	15.798 ± 0.091	16.640 ± 2.269
	c9 t11 18:2	–	0.065 ± 0.015
Linolenic	18:3 ω 6	0.102 ± 0.002	0.03 ± 0.015**
	18:3 ω 3	0.47 ± 0.005	0.32 ± 0.018***
Arachidic	20:0	0.227 ± 0.007	0.118 ± 0.018**
Eicosenoic	c11 20:1	0.180 ± 0.010	0.212 ± 0.008*
	c9 20:1	–	0.044 ± 0.005***
Eicosadienoic	c11 20:2	0.546 ± 0.015	0.424 ± 0.026**
Eicosatrienoic	20:3 ω 6	0.956 ± 0.012	1.040 ± 0.089
Arachidonic	20:4 ω 6	18.524 ± 0.434	16.046 ± 0.726*
Behenic	22:0	0.310 ± 0.008	–
Erucose	c9 22:1	0.147 ± 0.014	–
	c11 22:1	–	0.063 ± 0.017*
Eicosapentaenoic	20:5 ω 3	0.830 ± 0.021	0.634 ± 0.072*
Lignoceric	24:0	0.602 ± 0.035	0.175 ± 0.006***
Nervonic	24:1 ω 9	0.380 ± 0.019	0.165 ± 0.018***
Docosapentaenoic	22:5 ω 3	3.164 ± 0.117	2.942 ± 0.189
Docosahexaenoic	22:6 ω 3	1.144 ± 0.074	0.70 ± 0.077**
Saturated (SFA)		47.062 ± 0.500	44.878 ± 1.594
Monounsaturated (MUFA)		11.162 ± 0.129	16.524 ± 0.426***
Polyunsaturated (PUFA)		41.776 ± 0.607	38.598 ± 1.446

*Note: here and below, the difference is significant relative to the control group: * – $p \le 0.05$; ** – $p \le 0.01$; *** – $p \le 0.001$*

At the same time, a decrease in the level of stearic acid in the experimental group compared to the control group by 10.6% ($p < 0.05$) was detected, which may indicate an intensification of β-oxidation or a change in the metabolic pathways of the transformation of saturated fatty acids in the liver under the influence of essential oils contained in the studied feed additive.

In the experimental group, a significant increase in the content of monounsaturated fatty acids was observed. Thus, the level of palmitoleic acid increased almost twice ($p < 0.001$), which may indicate the active involvement of this fatty acid in energy metabolism and the formation of the lipid profile of the liver. In the liver of the experimental group, a significant increase (by 60.2%, $p < 0.001$) in the content of oleic acid was also recorded. This confirms previously obtained data on the effect of phytogenic supplements on increasing the level of MUFA, which can positively affect the quality of meat, in particular its tenderness and taste.

The presence of eicosenoic acid was found only in the liver of pigs in the experimental group, in the control group this acid was absent altogether. Such an increase in MUFA may indicate an increase in the mobilization processes of long-chain MUFA in the liver under the influence of essential oils.

The total proportion of MUFA in the liver of animals in the experimental group was 48.0% ($p < 0.001$) higher compared to the corresponding indicator in the control, which indicates a significant effect of the feed additive on lipid metabolism.

In the experimental group, a decrease in the level of some polyunsaturated fatty acids was observed, which may be due to their active use in metabolic processes or increased oxidation. For example, the level of linolenic acid (18:3 ω3) decreased by 31.9% ($p < 0.001$), and docosahexaenoic acid – by 1.63 times ($p < 0.01$).

The decrease in the proportion of ω-3 PUFAs can be explained by their increased incorporation into biological membranes and use in antioxidant protection processes, since the essential oils included in the feed additive have pronounced antioxidant properties. The level of arachidonic acid in the experimental group also decreased by 13.4% ($p < 0.05$), which may probably indicate a decrease in inflammatory processes, since this acid is a precursor of pro-inflammatory eicosanoids.

However, changes in the total content of PUFA in animals of the experimental group did not acquire a statistically significant difference ($p > 0.05$) compared to the control. The obtained data indicate a significant effect of the phytogenic feed additive "Activo" on the fatty acid composition of the liver of pigs.

Therefore, the most significant changes occurred in the content of MUFA, in particular, the level of oleic and palmitoleic acids increased, which may be a positive factor for the quality of meat. At the same time, a decrease in the concentration

of individual PUFAs, such as docosahexaenoic and linolenic acids, may be a consequence of their active involvement in oxidation.

The results obtained are consistent with the data of previous studies [13, 14], where it was also shown that essential oils can modulate the fatty acid composition of the liver and improve its antioxidant status.

9.3.2 Analysis of the fatty acid composition of pig tenderloin

Analysis of the fatty acid composition of pig tenderloin fed with the feed additive "Activo" showed significant changes in the content of saturated, monounsaturated and polyunsaturated fatty acids compared to the control group (**Table 9.2**).

In the experimental group, compared to the control group, a tendency to a decrease in the total level of saturated fatty acids was recorded. Using the example of individual SFA, a common dynamic is observed, characterized by a decrease in the content of these acids in the muscles of the experimental group. In particular, the level of pentadecanoic acid decreased by 1.87 times ($p < 0.001$) compared to the control group, margarine acid – by 1.82 times ($p < 0.001$), and stearic acid – by 14.4% ($p < 0.01$).

The decrease in the level of these fatty acids may be associated with the activation of β-oxidation processes in the skeletal muscles of animals receiving the phytogenic feed additive. At the same time, no significant changes in the content of the main SFA – palmitic acid – were recorded. Its level remained practically did not differ in the control and experimental groups, which indicates the stability of lipogenesis processes in muscle tissues regardless of the studied feeding factors.

The increase in the level of monounsaturated fatty acids in the muscles of pigs of the experimental group by 14.7% ($p > 0.05$) compared to the control group indicates an intensification of metabolic processes associated with the formation of MUFA. In particular, the level of palmitoleic acid increased by 23.5% ($p < 0.05$), which indicates an increase in its synthesis in response to feeding the feed additive. A significant increase was also found for oleic acid, the content of which increased by 16.3% ($p < 0.05$) compared to the control group, which is an indicator of an improvement in the fatty acid profile of muscle tissue, since oleic acid is associated with improved taste characteristics of meat. At the same time, an increase in the level of oleic acid isomers was also recorded: by 15.8% ($p < 0.01$) in animals of the experimental group compared to the control group. In addition, the level of eicosenoic acid in the experimental group decreased to 0% ($p < 0.001$), which may indicate its more intensive involvement in metabolic processes in the presence of phytogenic components.

Table 9.2 Fatty acid composition of tenderloin of pigs fed with the additive "Activo" ($M \pm m$, $n = 5$)

Fatty acid	Code	Groups	
		Control	Experiment
Capric	10:0	0.094 ± 0.011	0.116 ± 0.008
Lauric	12:0	0.142 ± 0.016	0.118 ± 0.013
Myristic	14:0	1.212 ± 0.024	1.306 ± 0.050
Pentadecanoic	15:0	0.142 ± 0.015	0.076 ± 0.009***
Palmitic	16:0	24.664 ± 0.262	24.836 ± 0.614
Palmitoleic	16:1	2.268 ± 0.080	2.800 ± 0.173*
Margarine	17:0	0.604 ± 0.037	0.332 ± 0.050**
Heptadecenoic	17:1	0.368 ± 0.026	0.202 ± 0.029***
Stearic	18:0	16.572 ± 0.309	14.182 ± 0.574**
Oleic	t 18:1	0.420 ± 0.018	0.222 ± 0.015***
	c9 18:1	29.236 ± 0.411	34.00 ± 0.508*
	c11 18:1	2.880 ± 0.086	3.334 ± 0.077**
	c12 18:1	0.102 ± 0.006	0.110 ± 0.008
Linoleic	c, t 18:2	0.100 ± 0.005	0.056 ± 0.014*
	18:2 ω 6	13.960 ± 0.271	13.634 ± 2.794
Linolenic	18:3 ω 3	0.634 ± 0.070	0.540 ± 0.063
Arachidic	20:0	0.162 ± 0.004	0.170 ± 0.003
Eicosenoic	c11 20:1	0.493 ± 0.023	0.562 ± 0.051
	c11 20:1	0.526 ± 0.040	0.0 ± 0.00***
Eicosadienoic	c11 20:2	0.366 ± 0.021	0.326 ± 0.020
Eicosatrienoic	20:3 ω 6	0.366 ± 0.022	0.308 ± 0.056
Arachidonic	20:4 ω 6	3.846 ± 0.285	2.226 ± 0.483*
	c11 22:1	0.0 ± 0.00	0.020 ± 0.006**
Eicosapentaenoic	20:5 ω 3	0.158 ± 0.015	0.080 ± 0.008**
	22:2	0.150 ± 0.036	0.0 ± 0.00**
Docosapentaenoic	22:5 ω 3	0.584 ± 0.049	0.312 ± 0.043**
Docosahexaenoic	22:6 ω 3	0.160 ± 0.013	0.158 ± 0.006
Saturated (SFA)		43.614 ± 0.298	41.136 ± 1.103
Monounsaturated (MUFA)		36.076 ± 0.495	41.378 ± 2.747
Polyunsaturated (PUFA)		20.310 ± 0.511	17.489 ± 3.207

A tendency to decrease the total proportion of PUFA in the tenderloin of animals of the experimental group compared to the control was established, which indicates a possible decrease in the need for these fatty acids due to the improvement of the antioxidant status of the animals. The level of arachidonic acid in the experimental group decreased by 1.73 times ($p < 0.05$) compared to the control, which may be in favor of reducing the level of inflammatory processes in muscle tissue under the influence of phytogenic supplements. A twofold decrease ($p < 0.01$) in the level of eicosapentaenoic acid was also established.

Similar changes were recorded for docosapentaenoic acid, the level of which in the muscles of animals in the experimental group decreased by 1.87 times ($p < 0.01$). The decrease in the content of ω-3 PUFA may be associated with their more active involvement in the antioxidant protection of muscle tissues in animals receiving the feed additive "Activo".

The results obtained indicate a significant effect of the feed additive "Activo" on the fatty acid composition of pork tenderloin. The main changes concerned an increase in the level of MUFA, in particular oleic acid, which may have a positive effect on the quality of meat, making it more tender and juicier. A decrease in the content of some PUFA was also noted, which may be associated with their active use in the processes of regulating inflammatory reactions and antioxidant protection. The results confirm previous scientific results [13, 14], according to which the use of essential oils in animal nutrition contributes to the improvement of the fatty acid profile of muscle tissue and enhances the antioxidant potential of the body.

9.3.3 Fatty acid composition of back muscles

Analysis of the fatty acid composition of the longest back muscle of pigs fed the feed additive "Activo" revealed significant changes in the balance of saturated, monounsaturated and polyunsaturated fatty acids, which may also indicate the effect of the phytogenic additive on lipid metabolism in muscle tissues (**Table 9.3**).

The results of the study showed that in the experimental group the total content of saturated fatty acids tended to increase, which may indicate an increase in the synthesis of saturated fatty acids or a decrease in their catabolism under the conditions of using the feed additive. Significant changes were observed in the concentration of individual SFA. Thus, the level of lauric acid under the influence of the additive decreased by 1.7 times ($p < 0.001$), which may be a consequence of its more active use as an energy source. At the same time, the content of palmitic acid, which is the main component of SFA, tended to increase, which may be associated with an

increase in the synthesis of this acid under the influence of biologically active substances of the feed additive. A similar trend was also found in the study of the content of stearic acid in the muscles of animals of the experimental group, which may indicate a change in the fatty acid profile of muscle tissue aimed at improving the stability of fat reserves.

The tendency to decrease the total content of MUFA in the longissimus dorsi muscle of the experimental group of animals compared to the control group may indicate the possible use of these fatty acids as energy substrates in metabolic processes. The same dynamics was established for oleic acid and its isomer in these muscles, which may be the result of more active β-oxidation or certain changes in the mechanisms of regulation of lipid metabolism.

The total proportion of PUFA in the longissimus dorsi muscle of the experimental group compared to the control group had a tendency to decrease, which may be associated with changes in the processes of lipid metabolism and antioxidant protection. A tendency to decrease in the content in these tissues was established for linoleic acid. The reasons for this decrease may be both its more active use in the synthesis of oxylipin derivatives and a change in the activity of enzymes responsible for its metabolism. In contrast, the level of arachidonic acid, despite changes in the overall balance of PUFA in the experimental group, remained practically unchanged compared to the control, which indicates the stability of its synthesis. A tendency to increase in content was also observed for docosapentanoic acid, which is a representative of omega-3 PUFA. This may indicate an increase in the metabolic activity of this class of fatty acids in response to feeding the feed additive.

The results of the study indicate that the addition of the feed additive "Activo" significantly affects the fatty acid composition of the muscle tissue of pigs, in particular the balance between saturated, monounsaturated and polyunsaturated fatty acids. The increase in the content of SFA, especially palmitic and stearic acids, may be associated with increased lipid synthesis under the influence of biologically active substances contained in the supplement. The decrease in MUFA levels is likely due to their increased metabolic utilization, particularly in β-oxidation. This is consistent with other studies [13, 14], which found that essential oils added to pig diets modulate the expression of genes involved in lipid metabolism, such as CPT-1 (carnitine palmitoyltransferase-1) and LPL (lipoprotein lipase).

The decrease in PUFA content, particularly linoleic acid, may be associated with a decrease in inflammation in muscle tissue, as derivatives of these acids are involved in the synthesis of pro-inflammatory prostaglandins [12]. The results obtained confirm the effectiveness of using phytogenic feed additives to improve the lipid profile of muscle tissue, which may positively affect the quality of meat products. Further

research is needed to determine the mechanisms of action of the active components of the "Activo" supplement at the level of cellular metabolism and their impact on the long-term quality of the product.

Table 9.3 Fatty acid composition of back muscles of pigs fed with the additive "Activo" ($M \pm m$, $n = 5$)

Fatty acid	Code	Groups	
		Control	Experiment
Capric	10:0	0.134 ± 0.011	0.118 ± 0.014
Lauric	12:0	0.160 ± 0.008	0.092 ± 0.008***
Myristic	14:0	1.292 ± 0.081	1.148 ± 0.064
Pentadecanoic	15:0	0.086 ± 0.004	0.084 ± 0.021
Palmitic	16:0	23.68 ± 1.179	26.494 ± 1.972
Palmitoleic	16:1	3.036 ± 0.318	2.702 ± 0.225
Margarine	17:0	0.240 ± 0.017	0.298 ± 0.031
Heptadecenoic	17:01	0.180 ± 0.026	0.136 ± 0.027
Stearic	18:0	12.97 ± 0.670	16.83 ± 2.583*
Oleic	t 18:1	0.226 ± 0.021	0.216 ± 0.015
	c9 18:1	34.732 ± 0.969	32.034 ± 2.216
	c11 18:1	3.606 ± 0.294	3.284 ± 0.255
Linoleic	c, t 18:2	0.050 ± 0.006	0.064 ± 0.013
	18:2 ω 6	15.05 ± 3.602	11.452 ± 2.759
Arachidic	20:0	0.162 ± 0.013	0.194 ± 0.28
Linolenic	18:3 ω 6	0.033 ± 0.007	0.037 ± 0.0025
	18:3 ω 3	0.332 ± 0.022	0.378 ± 0.051
Eicosenoic	c11 20:1	0.446 ± 0.034	0.478 ± 0.332
	c9 20:1	0.063 ± 0.029	0.067 ± 0.021
Eicosadienoic	c11 20:2	0.232 ± 0.027	0.282 ± 0.034
Eicosatrienoic	20:3 ω 6	0.298 ± 0.046	0.366 ± 0.084
Arachidonic	20:4 ω 6	2.534 ± 0.394	2.654 ± 0.673
Eicosapentaenoic	20:5 ω 3	0.128 ± 0.029	0.125 ± 0.032
Docosapentaenoic	22:5 ω 3	0.407 ± 0.052	0.512 ± 0.053
Saturated (SFA)		38.724 ± 1.924	45.258 ± 4.483
Monounsaturated (MUFA)		42.264 ± 1.520	38.904 ± 2.622
Polyunsaturated (PUFA)		19.010 ± 3.136	15.838 ± 3.635

The proportion of ω-3 and ω-6 PUFAs plays an important role in human health, in regulating inflammation and maintaining cardiovascular, neurological and metabolic health. For optimal ratios of ω-3 to ω-6 PUFAs, the ratio is 1:4, or even lower. These recommendations are explained by the fact that these acids compete for the same enzymes in metabolic pathways and produce lasting physiological effects: ω-6 fatty acids (especially linoleic and arachidonic acids) There is a tendency to reduce inflammation, throat blood and cell proliferation, and ω-3 (linoleic, docosapentaenoic, docosahexaenoic), however, exhibit anti-inflammatory, antithrombotic and neuroprotective effects.

Daily diets, therefore, have a very high ratio of ω-3:ω-6 fatty acids, around 1:15–1:20. This is due, in principle, to the significant production of vegetable oils (such as corn, soybean and sunflower) and the low production of fatty fish. This imbalance is associated with an increased risk of chronic diseases, such as cardiovascular diseases, obesity, type 2 diabetes, autoimmune diseases.

Analysis of the effect of the feed additive "Activo" on the ratio of ω3:ω6 PUFA in the studied tissues of pigs indicates its tissue specificity (**Fig. 9.1**).

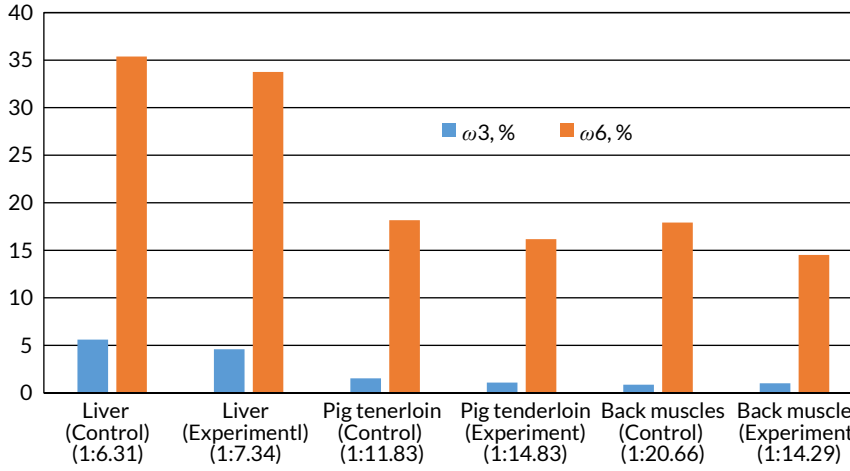

Fig. 9.1 The content of ω3 and ω6 fatty acids in the tissues of pigs fed with the feed additive "Activo" ($M \pm m$, $n = 5$)

The best ratio of these acids, which most closely meets the recommendations, was found in the liver of pigs in the control group. In the liver of animals in the experimental group, a synchronous tendency to decrease both ω-3 and ω-6 PUFA

was observed, but the deterioration of the ratio of these acids in the experimental group compared to the control group was insignificant and remained within the recommendations [21, 22]. In the muscle tissues of the tenderloin of pigs in the control group, the level of this ratio is inferior to the liver, but remains within the limits of a satisfactory assessment. Under the influence of the additive, a tendency to decrease the level of this indicator was also found in the tenderloin of animals in the experimental group.

However, in the back muscles, which among all the tissues studied were characterized by the lowest ratio of $\omega 3$:$\omega 6$ PUFA, under the action of the additive "Activo" there were significant positive changes in this indicator.

9.4 Conclusions

The results obtained indicate that the addition of the feed additive "Activo" to the diet of pigs affects the metabolism of fatty acids in various tissues. The most significant changes were recorded in the reduction of the level of polyunsaturated fatty acids in the liver by 4.6% ($p > 0.05$), in the tenderloin tissues by 5.7% ($p > 0.05$), and an increase in the proportion of monounsaturated compounds by 48.0% ($p < 0.001$), 14.7% ($p > 0.05$), respectively. In the long back muscle, there was an increase in polyunsaturated fatty acids by 16.9% ($p > 0.05$), and a decrease in monounsaturated compounds by 7.9% ($p > 0.05$). These changes may positively affect the quality of meat products. Changes in the composition of fatty acids in muscle tissues and liver may indicate an increase in the resistance of lipids to oxidation and an improvement in the organoleptic characteristics of meat. In the dorsal muscles of pigs under the influence of the supplement "Activo", in contrast to the decrease in the total content of unsaturated fatty acids, an increase in the proportion of ω-3 PUFA was observed, which contributed to an increase in the biological value of the lipid component of these muscles.

The results obtained confirm the effectiveness of using the phytogenic feed additive "Activo" to improve the lipid profile of muscle tissue, which may positively affect the quality of meat products. Further studies are needed to study the mechanisms of influence of biologically active substances of this feed additive on the regulation of lipid metabolism and its potential to increase pig productivity.

Thus, the use of feed additives based on essential oils is a promising direction for increasing animal productivity and improving the quality of the final meat product. Further studies should be aimed at studying the mechanisms of the influence of essential oils on lipid metabolism and determining the optimal doses of their use in pig diets.

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CHAPTER 10

Changes in quality parameters of sweet peppers during low-temperature storage after freezing

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Abstract

Low-temperature storage is a crucial method for extending the shelf life of sweet peppers while aiming to preserve their nutritional and sensory qualities. This study examined the impact of long-term low-temperature storage following freezing on the nutritional value, chemical composition, sensory attributes, and tissue microstructure of sweet pepper fruits. The content of colloidally bound water in sweet peppers significantly decreased from 23.6–26.7% to 9.2–9.4% after 270 days of storage, primarily due to freezing-induced damage, whereas the content of osmotically bound water increased from 66.3–69.0% to 83.3–83.5%. Soluble solids content in pepper fruits remained relatively stable throughout the storage period. Sugar content fluctuated, with some varieties exhibiting decreases of 0.9–6.5% and others increases of 1.4–1.5% after 270 days. Vitamin C and titratable acids declined progressively, with the Sonechko variety showing the greatest reduction in acid content (33.3%). Carotenoid levels in sweet peppers decreased by 17.2–17.8%, most notably at the onset of storage, while phenolic compounds – including anthocyanins, leucoanthocyanins, catechins, and flavonols – increased substantially. Pectin fractions demonstrated dynamic changes: water-soluble pectin initially increased by 41.8–80.9% within the first 10 days but declined by over 51% by day 270; protopectin rose by 101–123.6% after 90 days and remained elevated by 83.1–85.8% at the end of storage. Sensory evaluation revealed that the Atlant and Sonechko varieties retained favourable sensory and nutritional qualities, confirming their suitability for prolonged frozen storage. The freezing method significantly influenced pepper tissue microstructure; cryogenic freezing preserved tissue cohesion by producing small intracellular ice crystals, while cryoprotective solutions such as marinades effectively mitigated freeze-induced damage. These results provide practical insights

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for the food industry to optimise freezing and storage protocols, thereby enhancing the quality and shelf life of sweet pepper products.

Keywords

Sweet pepper, freezing, long-term storage, moisture content, biochemical composition.

10.1 Introduction

According to the research data of Ukrainian Research Institute of Nutrition, Biotechnology and Pharmacy, the majority of the Ukrainian population is deficient in vitamins (C, E, β-carotene, B vitamins, etc.) and minerals (Ca, Mg, Se, etc.), which is one of the causes of premature aging of the human body and the development of many diseases [1].

As reported by the WHO, the daily share of fresh fruit and vegetables in the diet should be 600–800 g. However, the seasonality of agricultural production, the high cost of imported fresh fruit and vegetable products in the markets of Ukraine in winter and spring, the existing traditional methods of their storage do not make it possible to fulfil this task.

Postharvest storage of fruits and vegetables at ambient temperature leads to increased ethylene production, which accelerates ripening, senescence, and spoilage, ultimately resulting in significant quality degradation and economic losses [2]. Fruit and vegetable products lose their nutritional value as early as 2 hours after harvesting, and closer to winter the loss of vitamin C and minerals is 20–30% [3]. In contrast, low-temperature storage effectively reduces the loss of colour, flavour, and texture, thereby slowing down physiological aging and preventing decay. According to S. Mi [4], cold-shock precooling is an effective and environmentally friendly technique for maintaining the postharvest quality of fresh fruits and vegetables.

In addition, the losses of fruit and vegetable products during storage without the use of artificial cold are 15–60% depending on the type of products. Refrigeration technologies for the processing and preservation of food raw materials, semi-finished products, and ready-to-eat foods have become an integral component of global strategies for the storage of current and reserve food supplies. This is supported by international programs of the United Nations (FAO, WHO) and UNESCO (MAB Projects No. 10, 11, 12, 14), which emphasize the importance of food security and stock preservation through the implementation of advanced refrigeration technologies. They have no alternative in storing food stocks [5, 6]. However, storing products sensitive to low temperatures – such as those of tropical and subtropical origin – in

a chilled state requires additional protective measures [7]. The criterion for evaluating different preservation methods is the extent to which they maintain the initial quality parameters of the raw materials, as well as the duration over which the method preserves the products with the desired properties. These requirements are best met by low-temperature freezing.

Low-temperature freezing significantly slows down biochemical processes in plant tissues and inhibits the growth of microorganisms that compromise product quality. Although freezing and frozen storage alter the initial mechanical properties of products, they effectively preserve their nutritional value [8]. Freezing of foodstuffs holds significant importance and offers extensive possibilities for preserving taste, appearance, and minimizing biochemical changes in seasonally produced products. This approach facilitates achieving a balanced diet in accordance with scientific recommendations and supports the operation of processing plants during off-season periods. It enables the delivery of frozen products across countries, playing a vital role in international trade, and ensures the provision of various regions with products that may be otherwise unavailable. Furthermore, frozen products are used in a wide range of industrial sectors and support the efficient processing of surplus harvests. This enables their long-term preservation for use during years of reduced agricultural yields, thereby helping to mitigate the impacts of natural disasters. Adopting freezing technology can reduce labour and time costs by up to 30 times in public catering systems and by up to 150 times in households. It also contributes to a 20–40% decrease in raw material losses, enhances microbiological and environmental safety, and reduces energy consumption by 50% compared to the production of sterilized canned foods. Furthermore, freezing permits the use of cost-effective, convenient, and practical packaging, improves product transportability, and facilitates the mechanization of manual labour processes [9–15].

10.2 Nutritional value of fresh sweet peppers

To optimise the frozen product range, it is necessary to select products that are the richest sources of easily digestible carbohydrates, fibre, pectin, vitamins, enzymes, minerals and other beneficial substances. These include sweet pepper. Sweet pepper (*Capsicum annuum L.*) is among the most economically important fruit vegetables, valued for its high nutritional content, appealing flavour, and vibrant colour [16]. However, its relatively short shelf life remains a key limitation in post-harvest handling and distribution. Its fruits contain up to 5% sugar (on raw matter),

1.5% protein, 0.95% fat, 0.5% potassium salts, 0.13% sodium, 0.16% iron (iron salts contribute to the increase of haemoglobin in the blood) and others. Specific pleasant flavour of pepper is determined by the presence of essential oils in it, the concentration of which ranges from 0.1–1.25% per dry matter.

The main advantage of pepper is that it provides a large group of vitamins. In terms of vitamin C content, it surpasses all other vegetable plants and, depending on variety, growing conditions and degree of maturity, contains an average of 100–400 mg per 100 g of raw matter.

The presence of vitamin P (140–170 mg per 100 g) in peppers enhances the biological effect of vitamin C by delaying oxidation and promoting full absorption. P-active substances are flavonols (85%), catechins (10%), anthocyanins (6%). Their content reaches a maximum at the beginning of fruit ripening, then decreases. Pepper fruits contain carotene (1.7–2.0 mg/100 g), B vitamins (thiamine 0.09–0.2 mg/100 g, riboflavin 0.02–0.1 mg/100 g), folic acid (0.1–0.17 mg/100 g), nicotinic acid (0.5–0.6 mg/100 g). It is enough 20–50 g of fresh peppers to meet the daily requirement of vitamin C and P.

Due to its nutritional value, peppers are widely grown on all continents of the globe. It is grown both in the open ground and in greenhouses. In Ukraine, sweet pepper is grown in greenhouses in limited quantities, because its yield due to biological features is much lower (8–10 kg/m^2) than cucumber (24–30 kg/m^2). Its production is primarily carried out on farms, totalling approximately 100 thousand tonnes per year, with around 19 thousand tonnes produced annually in the Zaporizhzhia region. The yield ranges from 200 to 460 cwt/ha, depending on the variety and agricultural practices [15, 17].

10.3 Characteristics of sweet pepper varieties

Pepper is one of the leading vegetable crops in Ukraine. It plays a crucial role as a raw material base for the canning industry and is widely used for consumption in both fresh and canned forms. Its rich chemical composition and harmonious flavour make it ideal for use in dietary and medical nutrition.

Pepper is an annual plant (it can be perennial in the tropics). The stem is short or medium-long. The flower is oviparous. The fruit is a 2–4 nested berry, depending on the variety it can have a shape – rounded, flattened, egg-like, spherical, cube-shaped, cone-shaped, cylindrical, pyramidal.

Pepper colour depends on ripeness and variety: in the phase of technical maturity, it can be light green, dark green, milky white, yellow, or violet-green. In the phase

of biological maturity (seed), it changes to red, orange-red, dark red, yellow, or orange. Seeds of pepper are yellowish-white, flat-rounded. The root system of pepper plants is highly branched. The characteristics of sweet pepper varieties are listed below [18, 19]:

1. The Lastivka variety was developed by the Moldavian Research Institute of Irrigated Agriculture and Vegetable Growing. It is a medium-ripening variety, with a period from sprouting to the first harvest at the stage of technical ripeness lasting 89–118 days, and up to 128–132 days for biological ripeness. The plant has a semi-spreading bush of medium height (42–53 cm). Fruits are cone-shaped, slightly oval, smooth, medium-sized, and weigh between 40–60 g. The pulp is sweet, with a thickness of 6–8 mm. The colour of the fruit at technical maturity is light green, while at biological maturity it is dark red. The yield is 223–487 cwt/ha.

2. The Aivenho variety was developed by PE "Agrosvit" and is a medium-ripening type. The vegetation period until the first harvest is 110–118 days. The plant forms a stem-type, semi-branched bush with a height of 53–68 cm. Fruits are cone-shaped, slightly ribbed, smooth, and medium to large in size, weighing between 75 and 98 grams. The pulp is sweet and 6–8 mm thick. The fruit is light green at technical maturity and turns red at biological maturity. The yield ranges from 230 to 520 cwt/ha.

3. The Atlant variety is a high-potential, medium-ripening type. The period from seedling emergence to the first harvest at technical ripeness is 90–120 days, and up to 132–136 days at biological ripeness. The plant forms a stem-type bush with a height of 55–70 cm. Fruits are cone-shaped, ribbed, large, and weigh between 120 and 150 grams. The pulp is sweet and 5–7 mm thick. The fruit is green at technical maturity and dark red at biological maturity. The yield ranges from 235 to 530 cwt/ha.

4. The Antei variety, developed by PE "Agrosvit", is a medium-ripening type. The vegetation period until the first harvest is 105–128 days. The plant forms a stem-type bush with a height of 70–90 cm. Fruits are cone-shaped with pronounced ribbing, very large, and weigh between 130 and 180 grams. The pulp is sweet and 4–7 mm thick. The fruit is green at technical maturity and dark red at biological maturity. The yield ranges from 270 to 540 cwt/ha.

5. The Sonechko variety is a medium-ripening type. The period from sprouting to technical ripeness is 110–120 days, and up to 140–150 days to reach biological ripeness. The plant is compact and stunted, with a height of 30–40 cm. Fruits are rounded, smooth, and non-ribbed; they are green at the stage of technical ripeness and turn orange-yellow at biological ripeness. The average fruit weight is 70–100 grams, with a flesh thickness of 6–8 mm. The yield ranges from 240 to 470 cwt/ha.

10.4 Tissue microstructure of sweet peppers after freezing

The effect of different freezing methods on the microstructure of pepper fruits was investigated using the following approaches:

– cryogenic environment: freezing in liquid nitrogen at –273°C and in liquid nitrogen vapour at –170°C;

– air environment: freezing in the air of a refrigeration chamber at –24°C with natural air circulation;

– liquid environment: freezing in a marinade, using plastic cups with a capacity of 0.250 dm^3.

To assess the damaging effect of ice on the cellular structure of tissues, histological studies were conducted on pepper fruits before and after freezing in different environments.

In **Fig. 10.1, *a*, *b***, the tissues of fresh sweet pepper fruits are shown. The cells in the longitudinal section appear more elongated and closely packed, with minimal intercellular spaces. In the transverse section, the cells appear more rounded, with the sides of the cell walls being 1.5–2.0 times smaller compared to the longitudinal section. The intercellular spaces are larger and more pronounced, and the cell walls remain undistorted.

Freezing in liquid nitrogen and nitrogen vapour resulted in a more cohesive cell structure, as small ice crystals formed inside the cells before noticeable dehydration of the cells occurred (**Fig. 10.1, *c*, *d***). When frozen in liquid nitrogen, the cells of various tissues, including the pulp, do not separate. While they maintain a healthy appearance, some areas show visible damage to the cell walls. Even with cryogenic freezing, a more precise selection of the freezing parameters is necessary, which calls for more advanced equipment.

However, it is known that application of ultrahigh freezing rates leads to irreversible changes in protein structures of the cell, as well as deterioration of the quality of frozen products due to the appearance of large cracks on the fruit surface (when freezing in liquid nitrogen **Fig. 10.1, *a***) and many microcracks (when freezing in nitrogen vapour **Fig. 10.1, *b***). This phenomenon occurs as a result of high internal stresses in the tissues, loss of plastic properties of the surface layers and expansion of the frozen inner layers of the product. The size of cracks also depends on the type and size of the frozen product. The larger the product and the higher the freezing rate, the greater the internal stresses, resulting in larger cracks.

Fig. 10.1, *d* clearly shows the structure of cells frozen using the traditional method in the air environment of the refrigerating chamber. Unlike the cells of fresh fruit, they have acquired an angular shape, likely due to the pressure exerted by

ice crystals formed in the intercellular spaces. Significant ruptures in the cell membranes of the fruit pulp, along with the formation of folds in the protoplasm and mechanical damage, are visible. According to S. Schudel et al. [21], the freezing of plant tissues with high moisture content frequently results in the formation of ice crystals that disrupt cellular structures. This damage contributes to drip loss and decreased tissue firmness, ultimately compromising the overall quality of the thawed product.

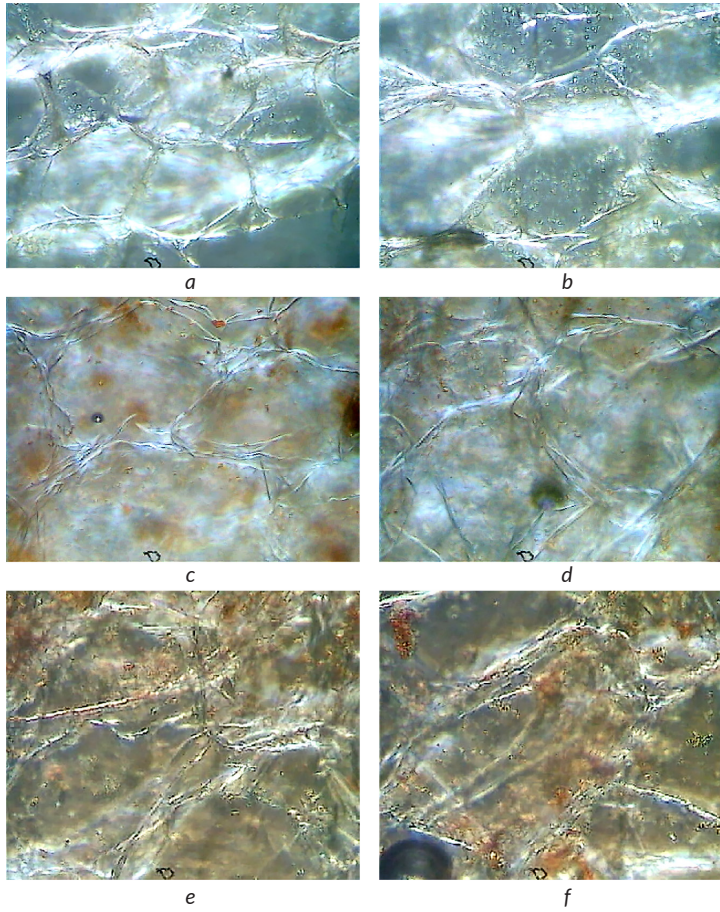
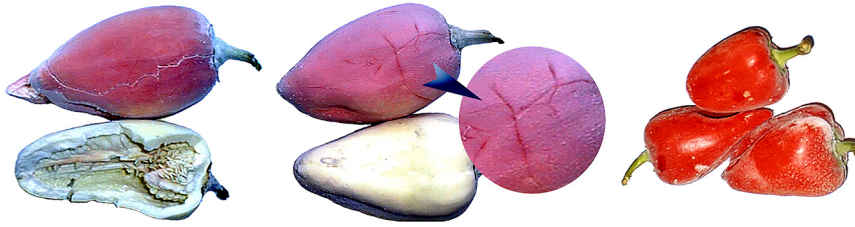


Fig. 10.1 Tissue microstructure of sweet pepper (Atlant variety): *a* – fresh – cross section; *b* – fresh – longitudinal section; *c* – frozen in liquid nitrogen; *d* – frozen in nitrogen vapour; *e* – frozen in bulk in a freezer; *f* – frozen dry in an air environment – defrosted

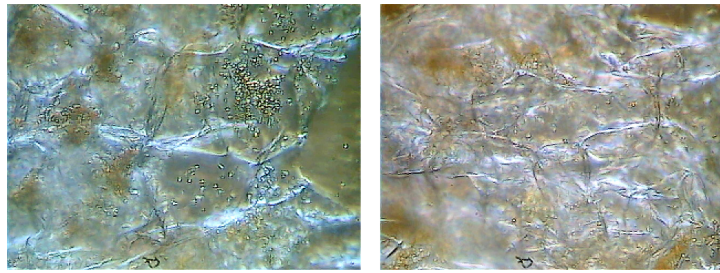
In **Fig. 10.1, *e*** the tissue microstructure of sweet pepper samples frozen in bulk in a freezer is presented, while in **Fig. 10.1, *f***, the sample frozen dry in an air environment and then defrosted is shown. **Fig. 10.2** illustrates the appearance of sweet peppers frozen using different techniques. Fruit frozen at a moderate rate had the best quality characteristics (**Fig. 10.2, *c***).



a *b* *c*

Fig. 10.2 Frozen pepper fruits in: *a* – liquid nitrogen; *b* – nitrogen vapour; *c* – air environment of the refrigerating chamber

There is very little information in the published papers regarding the effect of freezing on the tissue structure of fruits and vegetables frozen in solutions containing substances with cryoprotective effect. The microstructure of the pepper fruit parenchyma, frozen in a marinade, is similar to the structure of fruits frozen using the cryogenic method (**Fig. 10.3**).



a *b*

Fig. 10.3 Microstructure of pepper tissues frozen in marinade: *a* – Atlant variety; *b* – Sonechko variety

A comparative study of histological sections of peppers frozen using different methods showed that those frozen in a marinade produced a higher-quality product, with maximum restoration of cell shape, volume, and water content.

10.5 Quality parameters of sweet peppers during storage at low temperatures

The study of the chemical composition and sensory properties of sweet peppers was conducted on fruits frozen in the air environment of a freezing chamber at −24 ± 2°C (relative humidity 90–95%, air velocity 2.5–3.0 m/s) until their core temperature reached −20 ± 2°C, followed by storage for 270 days at −20 ± 2°C.

10.5.1 Content of water in sweet peppers during low-temperature storage

In plant tissues, water constitutes 70–95% of the raw mass. Even a slight reduction in the water content of pepper fruits leads to a noticeable loss of their natural freshness and firmness, thereby diminishing overall quality, shelf life, and market value [22].

According to the existing classification, two forms of water are distinguished: free water and bound water. Bound water is further subdivided into osmotically bound water, which is bound to ions (partially proteins and polysaccharides) and plays an important role in osmotic pressure in plant cells, and colloidally bound water, which is located inside colloidal systems, on the surface of colloids, and between them.

Free water is located in the intercellular spaces of the product and acts as a solvent for mineral substances. At temperatures below the cryoscopic temperature, it freezes into ice. As free water freezes, the concentration of salts in the unfrozen intercellular solution increases, causing a shift of its cryoscopic temperature to lower values. Bound water freezes at lower temperatures than free water.

The experiments revealed the dynamics of total moisture content, colloidally bound water, and osmotically bound water in sweet pepper frozen in bulk, measured before freezing and after 10, 90, 180, and 270 days of storage. Two sweet pepper varieties, Atlant and Sonechko, were used in the study. The results are presented in **Table 10.1**.

The content of colloidally bound water in fresh fruits was 26.7% in the Atlant variety and 23.6% in the Sonechko variety (**Table 10.1**). After 10 days of storage, it decreased to 19.1% and 13.8%, respectively, and by the end of the storage period (270 days), it further declined to 9.4% in the Atlant variety and 9.22% in the Sonechko variety. Thus, after 10 days of storage, the colloidally bound water content in the Atlant variety decreased by 28.5% compared to its initial level in fresh fruits, while in the Sonechko variety it decreased by 41.5% (**Table 10.1**). A similar trend

was observed throughout the storage period. After 180 days of storage, the water content decreased by 44.6% in the Atlant variety and by 48.2% in the Sonechko variety compared to the initial level. After 270 days of storage, the decrease was 64.8% and 60.9%, respectively.

Table 10.1 Water content in sweet peppers during low-temperature storage

Sweet pepper variety	Storage period, days	Total water content (moisture), %	Colloidally bound water content, %	Osmotically bound water content, %
Atlant	Fresh	93.00 ± 0.01	26.70 ± 0.00	66.30 ± 0.00
	10*	92.99 ± 0.48	19.10 ± 0.36	73.89 ± 0.46
	180*	92.95 ± 0.39	14.80 ± 0.57	78.15 ± 0.38
	270*	92.89 ± 0.34	9.40 ± 0.76	83.49 ± 0.32
	$HCP_{0.5}$	0.45	9.11	9.04
Sonechko	Fresh	92.60 ± 0.00	23.60 ± 0.00	69.00 ± 0.06
	10*	92.59 ± 0.43	13.80 ± 0.30	78.79 ± 0.15
	180*	92.53 ± 0.24	12.23 ± 0.21	80.30 ± 0.60
	270*	92.47 ± 0.38	9.22 ± 0.22	83.25 ± 0.30
	$HCP_{0.5}$	0.41	7.75	7.25

*Note: * after freezing*

The content of osmotically bound water also changed during freezing and low-temperature storage (**Table 10.1**). The content of osmotically bound water in the fruits of the Atlant variety was 66.3% before freezing and 83.49% at the end of storage (270 days). In the Sonechko variety, it was 69.0% before freezing and 83.25% at the end of storage. Thus, after 10 days of storage, its content increased relative to the initial level by 11.4% in the Atlant variety and by 14.2% in the Sonechko variety. By the end of the storage period (270 days), the increase reached 25.9% and 20.7%, respectively.

The reduction in colloidally bound water is primarily caused by the destructive effects of low temperatures during the freezing process. Under these external influences, gels convert into sols, and partially vice versa. As a result, the amount of osmotically absorbed water increases, although not in direct correlation with the decrease in colloidally bound water. In the fruits of both varieties, the total moisture content changes only slightly during freezing and storage. A slower decline in moisture content during the storage of pepper fruits was also reported by E. R. Bayogan et al. [23].

10.5.2 Sensory properties of sweet peppers during low-temperature storage

Sensory evaluation is the most significant method of determining the quality of both fresh and frozen products. In this case, the taste, aroma, colour, shape, consistency, packaging, labelling, and weight of the product are assessed.

Sensory evaluation of fresh and frozen pepper fruits was conducted after defrosting, until the temperature reached 2°C. Sweet peppers were evaluated both fresh and after 90, 180, and 270 days of storage. The sensory evaluation of sweet pepper samples was conducted by a group of specially trained experts. The 5-point hedonic scale (5 – like extremely, 4 – like moderately; 3 – neither like nor dislike, 2 – dislike moderately; 1 – dislike extremely) was used. An average score was calculated from the evaluation results to characterize the comprehensive sensory attributes of the pepper.

Table 10.2 shows that the Atlant and Sonechko varieties demonstrated the best performance both fresh and frozen. When fresh, they received scores of 5.0 and 4.98 points, respectively. The fruits of the Atlant variety were large in size, had a vibrant dark red colour, and featured a pulp thickness of 6 mm. The fruits of the Sonechko variety were orange-yellow in colour, had an equally attractive appearance, and a pulp thickness of 7 mm.

Table 10.2 Mean scores of sensory properties of sweet peppers

Sweet pepper variety	Storage period, days				
	Fresh	10	90	180	270
Atlant	5.00	4.44	4.52	4.60	4.42
Sonechko	4.98	4.36	4.44	4.54	4.38
Antei	4.86	4.16	4.16	4.12	4.24
Aivenho	4.84	4.26	4.18	4.18	4.26
Lastivka	4.98	4.36	4.02	4.34	4.38

The Atlant, Sonechko, and Lastivka varieties received high sensory scores in their fresh form – 5.00, 4.98, and 4.98, respectively (**Table 10.2**). These same varieties also received the highest ratings after 10 days of storage, with average scores of 4.44, 4.36, and 4.36, respectively. A slight change in fruit colour, softening of consistency, partial loss of aroma and flavour were noted. Similar, but more pronounced, changes were observed in the fruits of other varieties after 10 days

of storage: Aivenho scored 4.26, and Atlant scored 4.16. After 270 days of storage, the sensory properties of sweet peppers were evaluated as follows: Atlant – 4.42, Sonechko – 4.38, Lastivka – 4.38, Aivenho – 4.26, and Antei – 4.24.

As shown by the tasting evaluation results, changes in fruit consistency began to deteriorate immediately after freezing and continued through the first half of the storage period. This was due to water recrystallization in the fruit tissues, which led to the destruction of cell membranes and moisture loss during thawing. By the end of the storage period, this process had diminished, and the pulp consistency developed a more stable structure. According to the results of the sensory analysis, the Atlant and Sonechko varieties stood out most prominently in terms of colour, aroma, and flavour.

10.5.3 The effect of low-temperature storage on the chemical composition of sweet peppers

The freezing process significantly alters the biochemical characteristics of succulent plant products. Natural changes occur in the content of soluble solids, sugars, acids, vitamin C, polyphenols, carotenoids, aromatic compounds, and other chemical components. All sweet pepper varieties studied exhibited changes in soluble solids content during the freezing process (**Table 10.3**).

Table 10.3 Content of soluble solids in sweet peppers during storage, %

Sweet pepper variety	Storage period, days					
	Fresh	10	90	180	270	$HCP_{0.5}$
Atlant	6.10	6.32	6.18	6.10	6.00	0.38
Antei	5.90	6.08	6.10	6.00	6.00	0.38
Lastivka	5.76	5.80	5.80	5.74	5.70	0.56
Aivenho	5.92	6.00	6.04	6.01	6.00	0.42
Sonechko	7.40	7.51	7.50	7.44	7.41	0.50

During the first 10 days of low-temperature storage, the soluble solids content increased in all varieties compared to fresh peppers, specifically by 3.6% in the Atlant variety, 3.1% in Antei, 0.7% in Lastivka, 1.4% in Aivenho, and 1.5% in Sonechko (**Table 10.3**). These changes were caused by water crystallization within the parenchyma cells, leading to an increased concentration of dry matter. For comparison, during storage of peppers at a temperature of 10.61 ± 0.04°C and relative

humidity of 99.48 ± 0.31%, the soluble solids content also increased over an 8-day period, from an initial value of 6.04 to 7.20°Brix on the eighth day [24].

After 90 days of storage, the soluble solids content of peppers remained almost unchanged, decreasing by only 2.2% in the Atlant variety and by 0.1% in the Sonechko variety compared to the levels after 10 days of storage. During the same period, the soluble solids content in the Antei and Aivenho varieties increased by 0.3% and 0.7%, respectively. In the Lastivka variety, the amount of soluble solids remained at the same level as after 10 days of storage. After 270 days of storage, compared to fresh peppers, the soluble solids content in the peppers of the Atlant and Lastivka varieties decreased by 1.6% and 1.0%, respectively. In contrast, the soluble solids content increased in the Antei, Aivenho, and Sonechko varieties of peppers by 1.7%, 1.4%, and 0.1%, respectively.

Similar to the changes in soluble solids content, the sugar content in all pepper varieties increased after 10 days of storage (**Table 10.4**). In the Atlant and Aivenho varieties, the sugar content increased by 2.3% after 10 days of storage compared to fresh peppers. In the Sonechko, Lastivka, and Antei varieties, the increase was 2.2%, 1.4%, and 0.8%, respectively. By the end of the storage period, the sugar content compared to the initial level in fresh peppers decreased in the Atlant, Antei, and Sonechko varieties by 6.5%, 2.2%, and 0.9%, respectively. Meanwhile, in the Lastivka and Aivenho varieties, the sugar content increased by 1.4% and 1.5%, respectively.

Table 10.4 Content of sugar in sweet peppers during storage, %

Sweet pepper variety	Storage period, days					
	Fresh	10	90	180	270	$HCP_{0.5}$
Atlant	4.31	4.41	4.40	4.37	4.03	0.33
Antei	3.58	3.61	3.64	3.50	3.50	0.29
Lastivka	3.60	3.65	3.70	3.70	3.65	0.26
Aivenho	3.43	3.51	3.56	3.50	3.48	0.20
Sonechko	5.43	5.55	5.60	5.33	5.38	0.22

The content of organic acids in pepper fruits is relatively low and does not significantly influence their flavour. However, the amount of these acids is important for assessing the nutritional value of the fruits. In fresh fruits of all five varieties, the titratable acid content ranged from 0.19% to 0.27% (**Table 10.5**).

After 10 days of low-temperature storage, a decrease in titratable acid content was observed in all pepper varieties, ranging from 4.8% to 26.1% (**Table 10.5**).

However, in the Antei variety, this indicator increased by 5.3%. After 270 days of storage, a decrease in titratable acid content was recorded in all varieties, with the most significant reductions observed in the Atlant and Sonechko varieties – by 20.8% and 33.3%, respectively. For comparison, T. V. R. Rao et al. [25] found that the titratable acidity of pepper fruits decreased during 18 days of storage at both 10°C and 25°C.

Table 10.5 Content of titratable acid in sweet peppers during storage, %

Sweet pepper variety	Storage period, days					
	Fresh	10	90	180	270	$HCP_{0.5}$
Atlant	0.24	0.21	0.21	0.20	0.19	0.04
Antei	0.19	0.20	0.20	0.20	0.18	0.04
Lastivka	0.21	0.20	0.18	0.19	0.19	0.04
Aivenho	0.23	0.17	0.21	0.20	0.19	0.01
Sonechko	0.27	0.24	0.20	0.20	0.18	0.05

Sweet pepper fruits are among the vegetables richest in vitamin C content (**Table 10.6**). The highest amount of vitamin C is accumulated in fruits at the stage of biological maturity [19], while in overripe fruits, the ascorbic acid content decreases. In fruits at the technical maturity stage, the vitamin C content is 40–50% lower than in those at biological maturity.

Table 10.6 Content of vitamin C in sweet peppers during storage, mg/100 g

Sweet pepper variety	Storage period, days					
	Fresh	10	90	180	270	$HCP_{0.5}$
Atlant	220.10	201.90	190.50	179.10	167.00	0.77
Antei	189.51	156.40	145.00	136.00	127.40	0.38
Lastivka	162.80	141.32	136.00	119.43	108.36	0.20
Aivenho	187.01	163.31	151.83	138.00	129.65	0.41
Sonechko	214.00	195.80	188.84	178.41	157.65	0.71

According to the results, the ascorbic acid content in all five varieties of fresh peppers was high, ranging from 162.8 to 220.0 mg/100 g (**Table 10.6**). The highest vitamin C content was found in the Atlant and Sonechko varieties, with values of 220.10 and 214.00 mg/100 g, respectively. Throughout the entire storage period, a decrease in vitamin C content was observed. After 270 days of low-temperature storage, the vitamin C content had decreased by 24.1% to 33.4%, ranging from

108.36 to 167.00 mg/100 g. For comparison, during storage of peppers at a temperature of 10.61 ± 0.04°C and relative humidity of 99.48 ± 0.31%, the ascorbic acid content initially decreased from 1.055 to 1.023 g/kg FW by the fourth day of storage, and then increased to 1.074 g/kg FW by the eighth day [24].

The transformation of ascorbic acid in frozen fruits involves its oxidation to dehydroascorbic acid, and subsequently to 2.3-diketogulonic acid. The first compound remains physiologically active, while the latter is not effective from a nutritional standpoint. Despite the loss of ascorbic acid in pepper fruits during low-temperature storage, the residual content remains high. Compared to many other vegetables – even when fresh – the vitamin C content in sweet peppers is several times greater. This highlights the unique value of storing nutrient-rich vegetable crops like sweet pepper at low temperatures to preserve their high nutritional quality.

Humans cannot synthesise carotenoids and therefore depend entirely on their intake from food sources. Of the approximately 600 carotenoids currently identified, only around 50 exhibit vitamin A activity and are classified as provitamin A carotenoids. These compounds are present as pigments in foods such as red peppers, carrots, and pumpkins. β-carotene is considered the most effective provitamin A carotenoid. Moreover, β-carotene serves not only as a source of vitamin A but also fulfils important biological functions [20].

The carotenoid content in sweet pepper fruits of the two varieties, Atlant and Sonechko, during low-temperature storage is shown in **Table 10.7**. In fresh sweet pepper fruits, the carotenoid content was 22.5 ± 0.50 mg/100 g for the Atlant variety and 15.60 ± 0.14 mg/100 g for the Sonechko variety. During storage, the carotenoid content in both varieties decreased. After 270 days of storage, the content had declined by 17.2% and 17.8% for the Atlant and Sonechko varieties, respectively. Notably, a significant reduction was already observed after just 10 days of storage, with decreases of 13.8% for the Atlant variety and 16.5% for the Sonechko variety compared to the fresh samples. Thus, the most intensive loss of carotenoids in pepper fruits occurs during the initial stage of storage.

Phenolic compound content plays a crucial role in determining sweet pepper quality. Many of these phenolics, primarily belonging to the flavonoid group, exhibit notable biological activity, particularly P-vitamin (vitamin P) effects, which are most pronounced when combined with ascorbic acid. Sweet peppers are classified among vegetables with a high content of vitamin P.

Freezing of sweet pepper fruits resulted in an overall increase in the content of the analysed phenolic compounds (**Table 10.7**). In fresh sweet pepper fruits of the Atlant and Sonechko varieties, the anthocyanin content was 1.06 ± 0.15 mg/100 g and 1.10 ± 0.08 mg/100 g, respectively. In the Atlant variety, anthocyanin levels

increased significantly during storage, reaching 1.76 ± 0.17 mg/100 g after 90 days – a 66.0% increase compared to fresh samples. Following this peak, a gradual decline was observed, with the content decreasing to 1.53 ± 0.08 mg/100 g after 270 days of storage. Nevertheless, despite the decreasing trend after 90 days, the anthocyanin content after 270 days remained 44.3% higher than that in the fresh Atlant samples. In the Sonechko variety, the trend in anthocyanin content during storage was similar. After 90 days of storage, the anthocyanin content increased by 115% compared to the fresh samples, reaching 2.36 ± 0.07 mg/100 g. This was followed by a slight decrease, with the content measuring 2.32 ± 0.11 mg/100 g after 270 days of storage. Overall, low-temperature storage led to a substantial increase in anthocyanin content in sweet pepper samples.

Leucoanthocyanins are another type of flavonoid compound found in plants. Leucoanthocyanins were found in equal amounts in the fresh fruits of the Atlant and Sonechko pepper varieties, each containing 52.2 mg/100 g (**Table 10.7**). Throughout the entire period of low-temperature storage, their content increased. After 10 days of storage, the leucoanthocyanin content increased by 9.8% in the Atlant variety (red fruits) and by 1.0% in the Sonechko variety (orange-yellow fruits). As storage progressed, a marked increase in leucoanthocyanin content was recorded, reaching 99.70 ± 0.41 mg/100 g in the Atlant variety and 96.80 ± 0.07 mg/100 g in Sonechko by day 90. These values correspond to an increase of 91.0% in Atlant variety and 85.4% in Sonechko variety, compared to the fresh fruits. Thereafter, the leucoanthocyanin content continued to rise, although at a slower rate. After 270 days of storage, the content reached 100.80 ± 0.12 mg/100 g in Atlant variety and 109.50 ± 0.19 mg/100 g in Sonechko variety.

Catechins are a class of flavonoids, commonly found in a variety of fruits and vegetables, and are associated with numerous beneficial health effects. In fresh fruits of sweet pepper varieties Atlant and Sonechko, their content was 56.00 ± 0.25 mg/100 g and 55.60 ± 0.32 mg/100 g, respectively **(Table 10.7**). During low-temperature storage following freezing, the catechin content increased, reaching 136.8 ± 0.14 mg/100 g for Atlant and 135.3 ± 0.25 mg/100 g for Sonechko by day 270. Thus, over the 270-day storage period, the catechin content in the pepper fruits of Atlant and Sonechko varieties increased by 144.3% and 143.3%, respectively. The most pronounced increase in catechin content occurred between days 10 and 180 of storage.

Flavonols are a subclass of flavonoids, characterised by their yellow or yellow-green colour, and contribute to the overall pigmentation of many fruits and vegetables. The flavonol content in fresh fruits of sweet pepper varieties Atlant and Sonechko was 32.00 ± 0.48 mg/100 g and 35.00 ± 0.14 mg/100 g,

respectively (**Table 10.7**). During low-temperature storage following freezing, their (flavonols) content increased. Within the first ten days of storage, the flavonol content in the pepper samples increased by 5–9% compared to fresh fruits, with an increase of 8.1% for Atlant and 5.7% for Sonechko. During the subsequent storage period, a more pronounced increase in flavonol content was observed. After 270 days of storage, the flavonol content in the pepper fruits ranged from 95.80 to 101.30 mg/100 g. Therefore, over the duration of prolonged low-temperature storage (270 days), the flavonol content increased by 189.4–199.4% compared to the levels in fresh fruits.

The total flavonoid content in sweet peppers increased throughout the entire low-temperature storage period and, by day 270, had increased by 137.1–142.1% compared to their content in fresh pepper samples (**Table 10.7**). In particular, the total flavonoid content in fresh fruits of the Atlant variety was 141.26 ± 0.23 mg/100 g, increasing to 334.93 ± 0.16 mg/100 g after 270 days of storage. In the Sonechko variety, the initial content was 143.9 ± 0.27 mg/100 g, rising to 348.42 ± 0.29 mg/100 g after 270 days.

The increase in the total content of phenolic compounds of various groups in sweet peppers during low-temperature storage after freezing can be attributed to several factors. These include the decomposition of complex compounds formed by the interaction of different flavonoid groups, as well as the gradual transformation of the biochemical composition through oxidative and reductive reactions occurring in frozen products. Additionally, the freezing of water leads to a relative increase in the concentration of chemical substances. The synergistic action of vitamins C and P also appears to play a significant role. Phenolic compounds inhibit the oxidation of ascorbic acid, which in turn exerts a stabilising effect on bioflavonoids. Moreover, a portion of ascorbic acid exists in a bound form, forming complexes with phenolic compounds. The breakdown of these complexes may also contribute to the observed increase in flavonoid content.

Sweet pepper fruits are characterised by a relatively high content of pectic substances. The content of water-soluble pectin in fresh sweet pepper fruits of the Atlant and Sonechko varieties was 608.79 and 612.63 mg/100 g, respectively (**Table 10.7**). After freezing and 10 days of storage, the water-soluble pectin content increased by 80.9% in Atlant and 41.8% in Sonechko fruits. However, during further low-temperature storage, the content of water-soluble pectin decreased significantly. After 270 days, it was reduced to 295.70 ± 0.07 mg/100 g in Atlant and 290.56 ± 0.32 mg/100 g in Sonechko. Thus, by day 270 of storage, the water-soluble pectin content in Atlant and Sonechko fruits had decreased by 51.4% and 52.6%, respectively, compared to fresh samples.

Table 10.7 Content of carotenoids, phenolic compounds, and pectic substances in sweet peppers during storage, mg/100 g

Sweet pepper variety	Storage period, days	Carotenoids	Content of phenolic compounds					Content of pectic substances		
			Anthocyanins	Leucoanthocyanins	Catechins	Flavonols	Total flavonoid content	Water-soluble pectin	Protopectin	Total pectic substances
Atlant	Fresh	22.5 ± 0.50	1.06 ± 0.15	52.20 ± 0.29	56.00 ± 0.25	32.00 ± 0.48	141.26 ± 0.23	608.79 ± 0.15	367.60 ± 0.07	976.39 ± 0.11
	10	19.40 ± 0.14	1.11 ± 0.29	57.30 ± 0.32	66.00 ± 0.41	34.60 ± 0.14	159.01 ± 0.23	1101.1 ± 0.19	371.60 ± 0.12	1472.70 ± 0.16
	90	19.11 ± 0.08	1.76 ± 0.17	99.70 ± 0.41	96.20 ± 0.32	60.40 ± 0.35	258.06 ± 0.25	483.74 ± 0.26	738.80 ± 0.27	1222.54 ± 0.28
	180	18.83 ± 0.14	1.65 ± 0.15	99.70 ± 0.09	131.2 ± 0.25	83.42 ± 0.45	315.97 ± 0.31	347.50 ± 0.10	732.50 ± 0.25	1080.00 ± 0.16
	270	18.63 ± 0.26	1.53 ± 0.08	100.80 ± 0.12	136.8 ± 0.14	95.80 ± 0.14	334.93 ± 0.16	295.70 ± 0.07	673.25 ± 0.06	968.95 ± 0.06
Sonechko	Fresh	15.60 ± 0.14	1.10 ± 0.08	52.20 ± 0.32	55.60 ± 0.32	35.00 ± 0.14	143.9 ± 0.27	612.63 ± 0.08	500.80 ± 0.43	1113.43 ± 0.26
	10	13.02 ± 0.33	1.24 ± 0.14	52.70 ± 0.22	66.20 ± 0.19	37.00 ± 0.32	157.14 ± 0.29	868.60 ± 0.14	552.30 ± 0.16	1420.90 ± 0.15
	90	12.91 ± 0.05	2.36 ± 0.07	96.80 ± 0.07	97.80 ± 0.07	79.20 ± 0.08	276.16 ± 0.10	580.20 ± 0.14	1120.00 ± 0.04	1700.20 ± 0.09
	180	12.84 ± 0.10	2.34 ± 0.04	103.27 ± 0.19	131.2 ± 0.53	89.40 ± 0.24	326.21 ± 0.33	350.20 ± 0.12	1060.00 ± 0.23	1410.20 ± 0.18
	270	12.83 ± 0.15	2.32 ± 0.11	109.50 ± 0.19	135.3 ± 0.25	101.30 ± 0.31	348.42 ± 0.29	290.56 ± 0.32	930.70 ± 0.12	1221.26 ± 0.21

The content of protopectin in fresh sweet pepper fruits varied significantly, being 367.60 ± 0.07 mg/100 g for the Atlant variety and 500.80 ± 0.43 mg/100 g for the Sonechko variety (**Table 10.7**). After freezing and low-temperature storage for 10 days, the protopectin content in the sweet pepper fruits increased, specifically by 1.1% in Atlant and by 10.3% in Sonechko fruits compared to fresh samples. During further storage for 90 days, the protopectin content continued to rise, reaching 738.80 ± 0.27 mg/100 g in Atlant and 1120.00 ± 0.04 mg/100 g in Sonechko. This represented an increase of 101.0–123.6% compared to the protopectin content in fresh peppers. However, after more than 90 days of storage, the protopectin content in the fruits began to decrease. Specifically, after 270 days of storage, the protopectin content in Atlant fruits decreased compared to the content after 90 days, but remained 83.1% higher than in fresh samples. A similar trend in protopectin content was observed in the Sonechko variety, where after 270 days of storage, the protopectin content was 85.8% higher compared to fresh fruits.

The total content of pectic substances in fresh sweet pepper samples was 976.39 ± 0.11 mg/100 g for the Atlant variety and 1113.43 ± 0.26 mg/100 g for the Sonechko variety (**Table 10.7**). Freezing the pepper samples and storing them under low-temperature conditions for 10 days resulted in an increase in pectic substances content by 50.8% for Atlant and 27.6% for Sonechko, compared to fresh samples. During further storage, the Atlant variety experienced a decrease in pectic ubstances content, which after 270 days amounted to 968.95 ± 0.06 mg/100 g, representing a 0.8% reduction compared to the fresh samples. In the case of the Sonechko variety, the pectic substances content initially increased to 1700.20 ± 0.09 mg/100 g after 90 days of storage, but then decreased to 1221.26 ± 0.21 mg/100 g after 270 days, still showing an increase of 9.7% compared to the fresh samples. The decrease in the amount of water-soluble pectin corresponds to the softening of the fruit pulp consistency, while the increase in protopectin content is associated with the acquisition of considerable rigidity in the peripheral cell layers, as cell walls consist of approximately 30% pectin substances. The sharp increase in pectin substances due to freezing is likely caused by the formation of uronic acids as a result of the oxidation of monosaccharides.

Thus, the quality attributes of sweet pepper – both chemical composition and sensory properties – undergo changes during storage, which are influenced by the variety, storage conditions, and duration. Similarly, D. Tsegay et al. [26] reported that the postharvest quality and shelf life of sweet pepper fruits were affected by variety, harvesting stage, and storage period. As noted by E. R. Bayogan et al. [23], the visual quality of pepper fruits was significantly influenced by both the variety and the storage conditions.

10.6 Conclusions

Low-temperature storage following freezing had a significant impact on the nutritional value and quality of sweet peppers. The content of colloidally bound water in the pepper fruits decreased from 23.6–26.7% to 9.2–9.4% after 270 days of storage, primarily as a result of the destructive effects of low temperatures during the freezing process. In contrast, the proportion of osmotically bound water increased from 66.3–69.0% to 83.3–83.5%. Meanwhile, the soluble solids content remained relatively stable throughout the 270-day storage period of the pepper fruits.

During low-temperature storage, the sugar content in peppers fluctuated, increasing and decreasing at different stages. In some pepper cultivars, after prolonged storage (270 days), the sugar content decreased by 0.9–6.5% compared to fresh fruits, while in others, it increased by 1.4–1.5%. Throughout the entire storage period, the vitamin C content in sweet pepper fruits gradually decreased, reaching a reduction of 24.1–33.4% by the end of the 270-day storage period. Similarly, the titratable acid content decreased in all pepper cultivars during storage. The fruits of the Sonechko variety showed the greatest reduction, at 33.3%, compared to the level prior to storage.

Prolonged storage at low temperatures also affected the carotenoid content of pepper fruits, which decreased gradually throughout the storage period. This resulted in a reduction of 17.2–17.8% compared to initial levels in fresh fruits. The most intensive decline was observed at the start of the storage period. Conversely, the level of phenolic compounds increased during storage. The anthocyanin content of different pepper varieties fluctuated throughout the storage period, initially increasing and then slowly decreasing towards the end of the 270-day period. Nevertheless, even at this final stage, the anthocyanin content remained 44.3–110.9% higher than that of fresh fruit. Throughout the entire low-temperature storage period, the levels of leucoanthocyanins, catechins, and flavonols in sweet pepper fruits increased by 93.1–109.8%, 143.3–144.3%, and 189.4–199.4%, respectively, by day 270 compared to their initial levels in fresh fruits.

Regarding the pectin fractions, the content of water-soluble pectin in pepper fruits increased initially by 41.8–80.9% during the first 10 days of storage, but subsequently decreased by over 51.4–52.6% by day 270. The protopectin content in sweet pepper increased by 101–123.6% after 90 days of storage, but then began to decline; however, by day 270 it remained 83.1–85.8% higher than in fresh fruit.

Evaluation of the sensory attributes of sweet pepper fruits during long-term storage showed that the Atlant and Sonechko varieties retained favourable sensory and nutritional qualities, demonstrating their suitability for prolonged frozen storage.

It was also established that the freezing method had a significant impact on the microstructure of pepper tissue. Cryogenic freezing (using liquid nitrogen or its vapour) resulted in the formation of small intracellular ice crystals, which better preserved tissue cohesion and reduced cell separation. Freezing in cryoprotective solutions, such as marinades, also showed promise in maintaining a microstructure comparable to that achieved by cryogenic methods, indicating that cryoprotectants may effectively mitigate freeze-induced damage.

Future research should focus on optimising freezing parameters and investigating the use of natural cryoprotectants to further enhance the preservation of sweet pepper quality and microstructure during long-term low-temperature storage.

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CHAPTER 11

Sunflower lecithin as an alternative to soy lecithin: technological approaches to improving its rheological, sensory and functional properties

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Abstract

Soy lecithin remains the primary industrial source of lecithin; however, increasing concerns regarding its GMO origin have driven interest toward alternative sources. Among them, non-GMO sunflower lecithin has emerged as a high-quality and economically viable substitute. Despite its advantages, sunflower lecithin presents several technological drawbacks, including an intense flavor and odor, dark color, and high viscosity, which can lead to a plastic, non-flowable consistency.

The objective of this study was to develop technological strategies to produce decolorized, deodorized, and liquid sunflower lecithin. Deodorization was achieved by dissolving lecithin in ethyl alcohol at concentrations ≥ 40% (w/w), resulting in the complete removal of characteristic fatty, sweet, and nutty notes, while caramel and floral undertones became barely perceptible. This process led to the fractionation of lecithin into alcohol-soluble and alcohol-insoluble components. The use of absolute ethanol significantly reduced the yield of the alcohol-soluble fraction (from 23% to 13%).

Furthermore, it was found that the incorporation of specific diluents into wet gum prior to drying prevented the formation of a plastic consistency and ensured a stable liquid state during storage. Among the diluents tested, calcium salts proved to be the most effective. The optimal concentrations for maintaining lecithin liquidity were identified as follows: calcium acetate – 0.4%, calcium orthophosphate – 0.4%, and calcium chloride – 0.35%.

Decolorization conditions were also optimized, with the most effective parameters being 0.7% hydrogen peroxide (calculated as 100% H_2O_2), a temperature of 90°C, and a treatment time of 120 minutes. Under these conditions, the color value of sunflower lecithin decreased from 18 to 4–6 mgJ_2/100 cm^3.

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To evaluate the role of individual phospholipid groups in thermal darkening, fractionation was performed. Results indicated that phosphatidylcholines were most susceptible to darkening upon heating, followed by phosphatidylinositols, while phosphatidylserines and phosphatidylethanolamines exhibited the least color change. No correlation was observed between the sugar content of phospholipid fractions and their tendency to darken under thermal treatment.

Keywords

Sunflower lecithin, lecithin refining, resource-saving technologies, wet gum, color changes in lecithin, deodorization of lecithin, viscosity changes in lecithin, physicochemical properties of lecithin, lecithin quality parameters.

11.1 Introduction

Over the past few years, consumers have begun to redefine the desired attributes of food and dairy products. Lecithin combines a variety of technological functions with full safety for the human body. They are widely used in food, medical, cosmetic and other industries. Lecithins are effective emulsifiers, dispersers, antioxidants, anti-splattering, and releasing agents with application in multiple food systems [1].

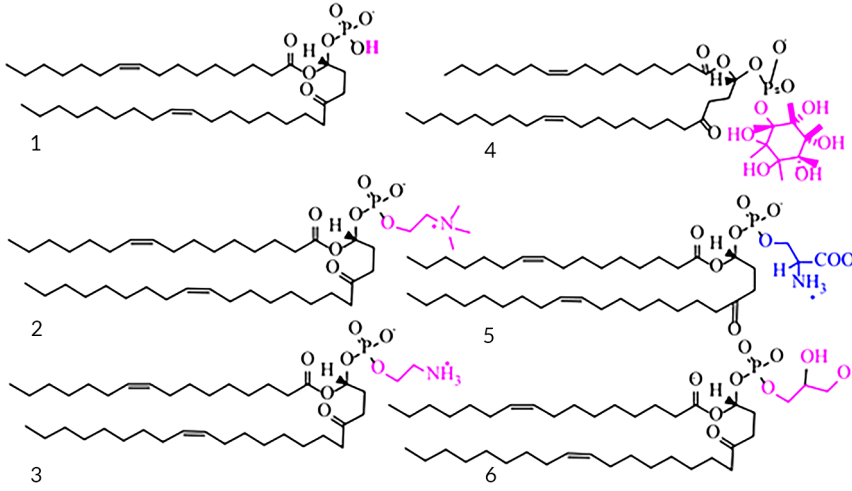
Lecithin is defined as a mixture of various phospholipids extracted from foods of different origins (animal or vegetable), containing at least 60% of acetone-insoluble substances [2].

The life of organisms without phospholipids is absolutely impossible. They deliver the necessary substances to the cells and remove the slag from them, take them in complex processes occurring inside the cage and between the cells, are the structural basis of all without exception of cell membranes, organelles, intracellular matrix. With age, as well as a result of various negative effects on the body (unfavorable ecology, stress, intense physical activity) cells are unable to synthesize phospholipids, causing cells to lose the ability to exchange metabolites with the environment and remove slag [3].

Known therapeutic and preventive effect of phospholipids in relation to several groups of diseases: hypercholesterolemia and hyperlipidemia, renal failure and diabetes [1]. Phospholipids have antioxidant effect, reducing the formation of toxic free radicals in the body (they have complex-forming properties and are able to inactivate heavy metal ions, as well as phospholipids prevent autoxidation) delay the development of cancers in 2 times. The second group of diseases includes all variants of liver pathology. The third group is neurological diseases – with regular intake of phospholipids, there is a gradual strengthening of the central nervous system:

the tendency to stress decreases, memory and productivity of thinking are improved [4]. The fourth is different cosmetic programs for correction of skin dryness, as well as some skin diseases. Lecithin can improve the texture of the skin by moisturizing it and reducing yellow fat deposits on the skin and around the eyes [5].

Commercial lecithins are mainly represented by products of plant origin – from soybeans, rapeseed, sunflower, corn, etc. Technologies for obtaining lecithins from egg yolk, brain, liver, etc. are known, but such commercial products are much more expensive. Lecithins from plant sources are represented mainly by glycerolipids (**Fig. 11.1**).



1 – phosphatidic acid, 2 – phosphatidylcholine, 3 – phosphatidylethanolamine, 4 – phosphatidylinositol, 5 – phosphatidylserine, 6 – phosphatidylglycerol

Fig. 11.1 Types of plant phospholipids
Source: [6]

The process of obtaining lecithin begins at the degumming stage, when water or an aqueous solution of acids is added to the unrefined oil or enzymatic degumming is carried out. The details of the degumming process, advantages and disadvantages of individual approaches are discussed in detail in [7]. As a result of this process, in addition to degummed oil, a wet gum is formed – a mixture of water, phospholipids and oil. It is microbiologically unstable, and to obtain a marketable product, water must be removed. As a result of gentle evaporation of water under low pressure, the final product is obtained – lecithin.

Degumming is possible due to the diphilic nature of phospholipid molecules. They contain a hydrophobic part – two fatty acid residues (R_1 and R_2, **Fig. 11.1**) and a hydrophilic part – glycerol and a residue of phosphoric acid esterified by a nitrogen group. When water (in quantities greater than 0.1%) enters the oil, phospholipids gradually concentrate on the surface of its droplets as a result of dissolving their hydrophilic part. Phospholipids and water form a dispersed phase and, due to their greater density than oil, precipitate into a precipitate called wet gum. However, phospholipid molecules also contain a hydrophobic part and also extract a significant amount of triglycerides into the wet gum. These are the so-called losses of neutral oil, which account for approximately 50% of the mass of extracted phospholipids.

Also, not all phospholipids are hydrophilic, i.e. those that are removed from the composition of oils by water. Phospholipids are also represented in non-hydrophilic forms. These are mainly complexes of phospholipids with metals. Phosphatidylinositol and phosphatidylcholine are completely eliminated in the process of aqueous degumming (under conditions of sufficient water, mixing of phases, etc.). Phosphatidic acid in an acidic environment forms complexes with metals and is not hydrophilic. It becomes hydrophilic in an alkaline environment. Phosphatidylethanolamine is non-hydrophilic only in a neutral environment [7]. Extracted oils contain much larger amounts of phospholipids that are not hydrated compared to pressed oils.

The reason for the difficulty of carrying out the degumming stage is that it is desirable to remove all groups of phospholipids from the oils and, at the same time, to remove the minimum amount of neutral oil.

A whole list of commercial phospholipid products is obtained from the wet gum obtained at the hydration stage of vegetable oils. Today, commercial preparations of vegetable phospholipids are divided into four main groups: standardized lecithins (with a phospholipid content of at least 50–60%), deoiled lecithins (phospholipid content of up to 98%), hydrolyzed lecithins (lysoforms of phospholipids, characterized by increased emulsifying effect), individual phospholipid fractions and technological functional composites based on lecithins (these are composites based on mono– and diglycerides of fatty acids (E 471), polyglycerol esters of fatty acids (E 475), lecithin (E 322), also on a protein basis) [8].

The technology for obtaining sunflower lecithin needs to be improved to increase its quality and production efficiency. The main disadvantages of sunflower lecithins include:

1) high content of mechanical impurities;

2) strong and characteristic (although pleasant) taste and smell;

3) high viscosity;

4) dark color;

5) slightly lower phospholipid content compared to soy lecithin and, related to this, slightly.

Let's consider these technological disadvantages and the results of research on their improvement separately.

11.2 Materials and Methods

11.2.1 Materials

Samples of sunflower lecithin containing 62.8% phospholipids, as well as a sunflower phospholipid emulsion, were provide by a Ukrainian manufacturer. Sunflower lecithin was characterized by the parameters summarized in **Table 11.1**. The emulsion had the following composition: water – 65.5%, phospholipids – 19.7%, and neutral lipids – 12.1%. Fractional composition: phosphatidylcholine – 15.8%, phosphatidylethanolamine – 7.5%, phosphatidylinositol – 13.9%, phosphatidic acid – 3.1%.

Table 11.1 Quality indicators of sunflower lecithin

Indicator	Sunflower lecithin
Mass fraction of substances insoluble in acetone, %	62.8 ± 0.8
Mass fraction of moisture and volatile substances, %	0.84 ± 0.02
Acid number of oil isolated from lecithin, mgKOH/g	5.9 ± 0.04
Peroxide value of oil isolated from lecithin, mmol1/2O/kg	3.05 ± 0.09
Mass fraction of substances insoluble in ethyl ether, %	0.6 ± 0.03
Viscosity at 25°C, Pa·s	10 ± 0.05
Color, mg of iodine	8 ± 0.1

The qualitative parameters of lecithins were assessed according to the national standard SOU 15.4-37-212:2004 "Phosphatide concentrates. Technical specifications".

11.2.2 Deodorization of sunflower lecithin

A 30 g portion of lecithin was dissolved in a mixture of ethyl alcohol and water (solvent ratio 96:4, 99.9:0.1, respectively). The samples were kept under constant

stirring (60 rpm) in a water bath at 60°C for 30 min, and then centrifuged at 1000 rpm for 10 min. Alcohol-insoluble and alcohol-soluble fractions were obtained, from which ethanol was eliminated by evaporation under reduced pressure to a volatile content of < 0.5%. The obtained fractions were stored at 10°C in a closed glass vessel and their sensory analysis was performed.

To conduct the organoleptic evaluation of sunflower lecithin, a tasting panel was formed, comprising 10 volunteers (5 men and 5 women aged between 23 and 60 years). All participants completed at least 10 hours of training aimed at developing skills to identify variations in the sensory characteristics of lecithins from different manufacturers at various storage stages, as well as for comparison with soy lecithins. Based on the training results, a sensory panel was developed, including the following typical aromas and flavors of lecithins: nutty, caramel, sweet, fatty, and fruity. The intensity of aroma was assessed using a five-point scale, where 1 represented minimal intensity and 5 corresponded to the intensity typical for fresh standard sunflower lecithin. Lecithin samples were placed in transparent glass containers (Petri dishes), which were sealed and labeled with coded numbers before evaluation. Prior to analysis, samples were heated to 50°C (the melting point of lecithin) and assessed under natural daylight conditions. Sample evaluation was randomized and conducted on different days.

The phospholipid fractional composition was analyzed by thin-layer chromatography using a solvent system of chloroform – acetic acid – water in a ratio of 70:36:4 on "Silufol-254" plates (Czech Republic).

11.2.3 Method for determining the rheological properties of sunflower lecithin

Samples of sunflower lecithin were initially heated above their melting point (exceeding 60°C), after which predetermined amounts of modifying agents, including sunflower oil, oleic acid, or ethyl oleate, were incorporated. Homogenization was performed in a water bath at 60°C using a propeller mixer operating at 120 rpm for 10 minutes. Following homogenization, the mixtures were cooled to ambient temperature and stored for 14 days before viscosity analysis.

For the preparation of sunflower phospholipid emulsions, designated volumes of diluents were added, and the mixtures were stirred at 60°C for 10 minutes. The resulting emulsions were subsequently dried using a rotary-film evaporator at 80°C under reduced pressure until the moisture content fell below 1%. The lecithin

concentrates obtained were cooled and stored at 5–10°C for 14 days to facilitate plastification processes, after which viscosity was determined.

The experimental procedure involved the use of 30% aqueous solutions of calcium salts, namely calcium chloride, calcium acetate, and calcium orthophosphate. Viscosity measurements were conducted using a Brookfield Viscometer LVT (USA) at 25°C, with the sample immersed in a thermostatic bath (TS-1/80 SPU). The measurement principle was based on determining the torque required to maintain a constant spindle rotation within the tested medium.

11.2.4 Method of extracting individual fractions from sunflower lecithin

In this work, a combined improved method was used, consisting of the following stages:

– method of degreasing phosphatide concentrate: isopropyl alcohol is added in small portions to a portion of sunflower lecithin at a ratio of 1:5 ÷ 6, respectively. The oil solution in isopropyl alcohol that has separated is separated from lecithin by filtering through a Buchner funnel, which is connected to a vacuum pump using a Bunsen flask. The degree of lecithin degreasing was recorded visually (light, non-sticky powder was obtained) and by grinding the powder on a calcine (it should not leave greasy traces);

– method of extracting the phosphatidylcholine fraction: 96% ethyl alcohol is added to the defatted lecithin (ratio 1:4). Mix thoroughly for 20 min. at a temperature of 50–60°C and leave to form a precipitate. The alcohol-soluble fraction is separated by decantation and volatile substances are distilled from it in a vacuum at a temperature not higher than 40°C. Then degrease again as described above, add ethyl alcohol again, decant the fractions and also distill the alcohol residues from the alcohol-soluble fraction. Fraction I is obtained, which contains mainly phosphatidylcholines. Ethyl alcohol is added twice more to the alcohol-insoluble fraction II, the alcohol-soluble fraction is separated and not used;

– method of extracting fractions of phosphatidylinositols and phosphatidylethanolamines: a portion of fraction II is dissolved in an eightfold excess of chloroform and the same amount of ethyl alcohol is added. Precipitate III (phosphatidylcholine fraction) is obtained. Fraction IV (a mixture of phosphatidylethanolamines and phosphatidylserines) is separated in the same way as in the previous methods. Further separation of phosphatidylethanolamines and phosphatidylserines was not performed due to their low separation coefficient (according to all known methods).

11.2.5 Method for determining the optical density of heat-treated lecithins

0.5 g portions of sunflower lecithin or its fractions with a known phospholipid content were dissolved in 9.5 cm^3 of refined sunflower oil and subjected to heat treatment at a temperature of 200°C for 2 hours. The samples were placed in heat-resistant glass test tubes with an expanded neck and hung on a tripod that was lowered into a bath filled with heat-resistant silicone oil. Constant stirring and temperature control within ± 0.1°C were maintained. Then, after cooling the test tubes, the optical density of the obtained samples was determined using an electrophotocalorimeter (KFK-2) relative to refined deodorized oil, which was added to the lecithin portions.

11.2.6 Method for decolorizing sunflower lecithin

A portion of lecithin (100 g) is placed in a round-bottomed flask and heated in a water bath (VB-4 MIKROMED) to a given temperature (70–90°C). Constant mixing of lecithin is carried out with constant stirring, without stopping the stirring, concentrated hydrogen peroxide (33%) is added in small portions and the reaction mixture is kept.

11.2.7 Statistical processing of experimental results

Analysis of variance (ANOVA) was used to determine the statistical significance of the effects of hydrogen peroxide content (X_1), duration of lightening (X_2) on lecithin clarification efficiency. 9 experiments were conducted in a given factorial space: X_1: from 1 to 5% hydrogen peroxide (33%); X_2: from 30 to 90 min. The range of variation was chosen based on previous experiments.

The data were analyzed using three-way ANOVA to assess: the effect of each independent variable (X_1, X_2), two-factor interactions (X_1X_2). The significance level was $\alpha = 0.05$.

The results of the experiment are a regression equation of the form

$$Y = b_0 + b_1X_1 + b_2X_2 + b_{12}X_1X_2,$$

where Y – color number of lecithin, mg J_2/100 cm^3; b_0 – intercept; b_1, b_2, b_{12}, b_{23}, b_{23} – interaction coefficients.

At 4 points, the calculated response value (Y – color number of lecithin) was determined according to the obtained regression equation. Experimental studies were conducted at the same points (with the same values of the parameters X_1, X_2). The obtained values of the experimental results and the theoretical ones (according to the regression equation) were compared and the coefficient of determination (R^2) value was established. In this way, it was assessed how well the model describes the obtained results. In scientific and technical research, $R^2 > 0.70$ is usually considered acceptable. Mathematical modeling was carried out using the Python programming language and the Sklearn libraries to determine the regression equation and Scipy for optimization.

The samples were randomized and tested on different days, with all measurements repeated three times. The statistical significance of differences between the mean values of all measurements was assessed at a significance level of $p < 0.05$ (5%).

11.3 Results

The possible high content of mechanical impurities in sunflower lecithin (insoluble in hexane or insoluble in toluene, or insoluble in ethyl ether according to the standards of different countries) is a known problem. However, it is solved by effective filtration of the oil before refining (separators are used for this purpose). Therefore, there is no need to investigate the removal of mechanical impurities from lecithin in this study.

11.3.1 Deodorization of sunflower lecithin

Deodorization of lecithin is a complex process. The industrial method of lipid deodorization is based on the different volatilities of triacylglycerols and other fat components, the total concentration of which can reach 5%. These include fatty acids, pigments and volatile compounds. This process is carried out at high temperatures (220–260°C), low pressure (3–5 mPa) and in the presence of 3–5% of acetic steam as a solvent for volatile components [9].

However, this approach is not suitable for lecithins, since they are thermolabile and prone to melanoidin formation, oxidation and other undesirable reactions. High temperatures cause oxidation of fatty acids, the formation of Maillard reaction products and the formation of aldehydes, which negatively affects the quality of lecithin. This leads to darkening of the product and the appearance of unpleasant odors, such as burnt or rancid [10].

Most of the volatile compounds contained in lecithins are products of autocatalytic decomposition of unsaturated fatty acids of phospholipids. The main source of the undesirable odor of defatted soy lecithin is isophorone, which is likely formed as a result of contact of lecithin with acetone. In addition, nitrogen-containing substances, including nitriles, acetoxime and 4.5-dimethylisoxazole, have been identified among the unique volatile compounds of phospholipids [10]. Among the volatile components of lecithin, aldehydes are characterized by the lowest perception thresholds, therefore, they are most likely to significantly affect the sensory characteristics of lecithins.

A feature of ethyl alcohol is its high selectivity with respect to substances that give lipids taste and odor (aldehydes, ketones, hydrocarbons, etc.). When lecithins are treated with ethyl alcohol, they are fractionated into an alcohol-insoluble fraction (mainly containing phosphatidylcholine) and an alcohol-insoluble fraction (mainly containing phosphatidylinositol, phosphatidic acid). Phosphatidylethanolamine is contained in both fractions. Since different phospholipids have different properties, lecithin is usually fractionated with solvents to obtain fractions with the desired functionalities.

During our own research on fractionation of sunflower lecithin, the effect of deodorization of the alcohol-soluble fraction was noticed. This result requires additional research. 5, 10, 20, 30, 40, 50% of 96% ethyl alcohol was added to sunflower lecithin. The results of the change in the sensory characteristics of the alcohol-insoluble fraction were as follows:

– when adding 30% ethanol (by weight to lecithin), the intensity of the lecithin odor significantly decreased;

– when adding 40% and higher amounts of ethanol, the odor and taste of sunflower lecithin could not be identified (**Fig. 11.2**).

The removal of odorants from lecithin is likely to occur by eliminating them in a mixture with ethanol.

The qualitative characteristics of the obtained lecithin are given in **Table 11.2**. Treatment of sunflower lecithin with 96% ethyl alcohol in an amount of 40% relative to lecithin leads to the formation of an alcohol-soluble fraction (phosphatidylcholine) in an amount of 23% and an alcohol-insoluble (phosphatidylinositol) in an amount of 77%.

The alcohol-insoluble fraction meets the requirements of the regulatory document. The alcohol-soluble fraction must be degreased to increase the content of acetone-insoluble substances. It was treated with acetone at a ratio of alcohol-soluble fraction:acetone as 1:1. As a result, the content of phospholipids in it increased to 63%.

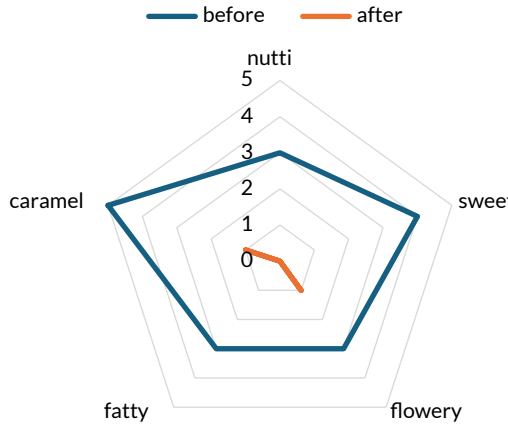


Fig. 11.2 Sensory characteristics of sunflower lecithin before and after treatment with ethyl alcohol (40% relative to lecithin)

Table 11.2 Qualitative indicators of lecithin fractions obtained as a result of treatment with 96% ethyl alcohol

Qualitative indicator	Requirements of the Ukrainian standard SOU 15.4-37-212:2004	Alcohol-insoluble fraction	Alcohol-soluble fraction
Mass fraction of substances insoluble in acetone, %	≥ 60	72.4 ± 0.4	25.5 ± 0.2
Mass fraction of moisture and volatile substances, %	≤ 1.0	0.38 ± 0.04	0.11 ± 0.02
Mass fraction of substances insoluble in ethyl ether, %	≤ 1.5	0.30 ± 0.04	0.30 ± 0.05
Acid number of oil isolated from lecithin, mgKOH/g	≤ 10	3.8 ± 0.05	5.2 ± 0.06
Peroxide value of oil isolated from lecithin, mmol1/2O/kg	≤ 10	1.8 ± 0.05	2.5 ± 0.06
Color, mg of iodine	≤ 8	4 ± 0.1	6 ± 0.2

The alcohol-soluble fraction after evaporation of ethyl alcohol also significantly reduced the intensity of the aroma. However, to a lesser extent compared to the alcohol-insoluble. Nevertheless, the intensity of the smell (2 on the developed scale) of the alcohol-soluble fraction is no more than that of soy lecithin. The qualitative indicators of the resulting product meet the requirements for fractionated phospholipid products [11].

The presence of water in ethyl alcohol affects the dissolution of phospholipids and related compounds in it. In order to reduce the yield of the alcohol-soluble fraction, sunflower lecithin was treated with 99.9% absolute ethyl alcohol (in amounts of 5, 10, 20, 30, 40, 50% relative to lecithin). The effect on the sensory characteristics of lecithin is the same as that of 96% ethyl alcohol. The deodorizing effect was also observed at 40% absolute ethanol. The yield of the alcohol-soluble fraction compared to the use of 96% ethyl alcohol under the same conditions is significantly reduced – from 23% to 13%, respectively. Thus, in order to reduce lecithin fractionation, it is advisable to use 99.9% ethyl alcohol. The fractional composition of the obtained lecithins (preliminarily defatted) is given in **Table 11.3**.

Table 11.3 Fractional composition of phospholipid products obtained after deodorization of sunflower lecithin with ethyl alcohol

Faction name	Composition, %			
	Ethyl alcohol-rectified		Ethyl alcohol, absolute	
	Alcohol-insoluble fraction	Alcohol-soluble fraction	Alcohol-insoluble fraction	Alcohol-soluble fraction
Phosphatidylcholine	10.5 ± 0.06	40.3 ± 0.9	12.8 ± 0.1	43.6 ± 1.0
Phosphatidylinositol	14.6 ± 0.1	9.8 ± 0.7	14.0 ± 0.9	7.7 ± 0.5
Phosphatidylethanolamine	21.8 ± 0.9	11.9 ± 0.1	22.6 ± 0.8	8.3 ± 0.7
Phosphatidic acid	8.9 ± 0.5	8.8 ± 0.4	8.5 ± 0.3	7.1 ± 0.4

The alcohol-soluble fraction meets the requirements for fractionated lecithins in terms of choline content (according to regulatory requirements – from 39%) and inositol (up to 3%).

The fraction enriched with phosphatidylcholine is characterized by improved emulsifying properties for oil-in-water (o/w) emulsions, which are necessary for the food, pharmaceutical and cosmetic industries. Such products are in wide demand. The fraction enriched with phosphatidylinositol is considered a high-quality emulsifier for water-in-oil emulsions.

11.3.2 Reducing the viscosity of sunflower lecithin

Sunflower lecithin is always liquid after production (drying wet gum), but after a few days it plasticizes and ceases to be liquid. This is inconvenient for its transportation, unloading, dosing and use in various food technologies, for uniform distribution

in food products, etc. Therefore, most buyers require a liquid state of lecithin, including sunflower. This corresponds to a viscosity value of 8–12 Pa·s. Sunflower lecithin has a higher viscosity than soybean and rapeseed due to the presence of long-chain waxes. Liquid lecithins, as a rule, correspond to Newtonian characteristics. An increase in the content of phospholipids gives an increase in viscosity, oils – vice versa. The highest viscosity of sunflower lecithin during its drying is observed at a water content of 0.7%. The presence of salts reduces the viscosity of lecithins [12]. The cheapest and safest diluent is table salt, but it increases the value of the "mechanical impurities" indicator, because it does not dissolve in either hexane or ethyl ether.

In order to determine the optimal conditions for obtaining liquid sunflower lecithin, diluents of different types were used. Related substances of lipid nature with lower viscosity were added to lecithin – sunflower oil, oleic acid and ethyl ester of oleic acid. Another way is to use salts of divalent metals, calcium derivatives were used as an element that is vital for the human body: chloride, acetate and calcium orthophosphate. According to our studies, the introduction of diluents into already plasticized lecithin

The results are given in **Table 11.4** (column 2).

Diluents were incorporated into the wet gum (produced by the same manufacturer as the sunflower lecithin), followed by drying under reduced pressure. The goal was to reach a final moisture content of approximately 0.7%, a level at which lecithin is most likely to undergo plasticization. The lecithin samples with added diluents were then stored for 14 days to enable potential plasticization processes. After this storage period, viscosity measurements were performed, and the results are presented in **Table 11.4** (column 3).

Comparing the data of columns 2 and 3 of **Table 11.4**, it can be concluded that the introduction of diluents should be carried out in a wet gum. In this case, the effective amount of diluents (to achieve a viscosity of 12 Pa·s) can be halved.

Table 11.4 The amounts of diluents required to reduce the viscosity of already plasticized sunflower lecithin (column 2) and lecithin obtained from wet gum to 12 Pa·s (at 25°C)

Diluent	Quantity, % in relation to sunflower lecithin	
Sunflower oil	26 ± 0.6	14 ± 0.4
Oleic acid	11 ± 0.2	6 ± 0.1
Ethyl ester of oleic acid	10 ± 0.3	4 ± 0.09
Calcium chloride	0.7 ± 0.03	0.35 ± 0.01
Calcium acetate	0.8 ± 0.04	0.40 ± 0.01
Calcium orthophosphate	0.8 ± 0.04	0.40 ± 0.01

The use of sunflower oil cannot meet the requirements of modern standards for sunflower lecithins due to the excess of the content of neutral lipids in lecithin. In the work, lecithin with an acetone-insoluble (phospholipid) content of 62.8% was used. The introduction of 14% of sunflower oil leads to a triglyceride content in lecithin of 49%. The amount of acetone-insoluble substances is thus less than 60%, which is unacceptable in the production of competitive natural lecithin.

Oleic acid and its ethyl esters are more effective in reducing the viscosity of lecithin, but they are quite expensive substances. Also, 6 and 4%, respectively, again underestimate the phospholipid content to a value of less than 60%. Thus, the optimal use of calcium salts is. Both chloride and acetate and calcium orthophosphate are known food additives permitted for use in the food industry in these quantities. All three of these diluents should be recommended for use in industry.

It is necessary to determine whether the recommended diluents do not negatively affect the quality indicators of sunflower lecithin. 0.4% of calcium orthophosphate was introduced into the wet gum, the quality indicators were established after drying. In parallel, the wet gum was dried without the introduced diluent. The results are given in **Table 11.5**.

Table 11.5 Quality indicators of dried sunflower lecithin

Indicator	Sunflower lecithin with calcium orthophosphate content of 0.4%	Sunflower lecithin	Requirements of SOU 15.4-37-212: 2004 "Phosphatide concentrates. Specifications"
Mass fraction of substances insoluble in acetone, %	62.8 ± 0.09	62.8 ± 0.1	≥ 60
Mass fraction of moisture and volatile substances, %	0.73 ± 0.05	0.85 ± 0.04	< 1.0
Acid value of oil isolated from lecithin, mgKOH/g	5.6 ± 0.11	5.4 ± 0.09	< 35
Peroxide value of oil isolated from lecithin, mmol1/2O/kg	2.8 ± 0.18	3.4 ± 0.10	≤ 10
Mass fraction of substances insoluble in ethyl ether, %	0.6 ± 0.10	0.6 ± 0.13	≤ 1.5
Viscosity at 25°C, Pa·s	10 ± 0.20	18 ± 0.26	≤ 12
Color, mg of iodine	6 ± 0.50	10 ± 0.55	≤ 8

The obtained sunflower lecithins with the recommended content of calcium acetate and calcium orthophosphate were stored at a temperature of 10°C (at this temperature, the maximum probability of forming a plastic consistency is) for 0.5 year. The lecithins were constantly in a liquid state, and their plasticization was not observed.

11.3.3 Sunflower lecithin clarification

Lecithin can be found in various colors and forms, ranging from light brown to dark reddish brown [13]. Dark brown color (sunflower lecithin) or a yellow-amber color (soybean lecithin).

The use of sunflower lecithin due to its dark color (color number is 18 mg J_2/100 cm^3 and above) is not possible in all food products, but only in dark-colored products. Therefore, the clarification of the establishment of optimal conditions for obtaining light sunflower lecithin is an important task. It is also of interest to determine the causes of lecithin darkening under the influence of elevated temperatures. It is known that the darkening of phospholipids during heat treatment is associated with the appearance of melanophospholipids – "brown pigments". There are several theories explaining the mechanism of their appearance, most of which point to: the interaction of phospholipids with free fatty acids and sugars with the formation of amines (this reaction occurs at temperatures below 80°C); the interaction of hydroperoxides and amino groups of phosphatidylethanolamine with the formation of imine; the reaction of adol condensation of phosphatidylcholine with the formation of macromolecular brown products (the reactions occur at temperatures higher than 80°C).

The corresponding part presents the developed method for separating sunflower lecithin fractions, the method for heat treatment of fractions and determination of optical density.

It turned out that the fractions of phospholipids, according to the degree of change in their color after heat treatment, create the following series: phosphatidylcholines – phosphatidylinositols – phosphatidylserines and phosphatidylethanolamines (**Fig. 11.3**).

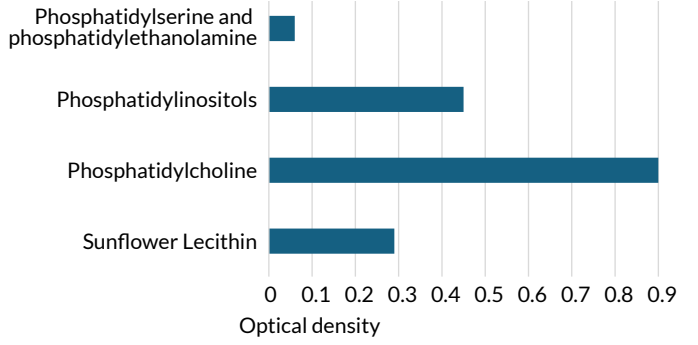


Fig. 11.3 Optical density of sunflower lecithin and its fractions after heat treatment

It is known that the content of sugars in phospholipids also leads to their darkening [14]. Therefore, to establish the probable influence of sugars on the degree of darkening of individual phospholipid fractions, their content in each of the fractions was determined. As can be seen from the data given in **Table 11.6**, there is no correlation between the values of the sugar content in the fractions and the optical density of the latter.

Thus, it is proven that the color of phosphatide concentrates at elevated temperatures is explained mainly by the influence of the phosphatidylcholine fraction.

Table 11.6 The content of phospholipids and sugars in the isolated fractions of sunflower lecithin

Faction name	Optical density after heat treatment	The content of the phospholipid fraction,% in relation to the total content of acetone-insoluble	Sugar content, %
Sunflower lecithin	0.29	–	0.044
Phosphatidylcholine	0.90	45.1	0.028
Phosphatidylinositols	0.45	21.2	0.051
Phosphatidylserine and phosphatidylethanolamine	0.06	48.9	0.045

Hydrogen peroxide is highly effective in decolorizing lecithins. A negative consequence of its use is a significant increase in the content of peroxide compounds. But some enzymes have a high ability to break down these compounds [15].

To reduce the number of experiments and increase the reliability of conclusions, it is advisable to use experimental planning methods. An active experiment of type 2^3 was conducted. The following factors were selected as the experimental factors: X_1 – concentration of 33% hydrogen peroxide, %, X_2 – duration of decolorization, min. and X_3 – temperature, °C. The response parameter is the color number, which was checked using the standard method. The model obtained as a result of calculating the factorial experiment data adequately describes the process of decolorizing lecithin with hydrogen peroxide. The regression equation is:

$$Y = 6.575 - 1.075x_1 + 1.075x_2 + 0.675x_3 - 0.275x_1x_2 - 2.475x_1x_3 + 1.675x_2x_3,$$
$$R^2 = 0.58.$$

Analysis of the obtained regression equation shows that all factors are significant, and the process of decolorization of sunflower lecithin should be carried out in accordance with the following conditions: process temperature – 90°C; amount of hydro-

gen peroxide (in terms of 100% peroxide) – 1%; duration of decolorization – 90 min. During the experiment, it was decided that hydrogen peroxide should be added in small portions to the lecithin already heated to 90°C with constant stirring. Under such conditions, the color number of lecithin decreases from 18 mg J_2/100 cm^3 to 4–6 mg J_2/100 cm^3.

During the research, it was recorded that by increasing the duration of decolorization, the same results can be obtained while simultaneously reducing the amount of hydrogen peroxide. Therefore, it was decided to decolorize lecithin under the same conditions, but with the addition of 0.5; 0.7; 1.0% hydrogen peroxide (in terms of 100% peroxide) and duration of decolorization – 90; 120; 180 min.

It was decided to introduce hydrogen peroxide into the wet gum before drying it. In this case, the unreacted peroxide will decompose under the influence of the high drying temperature.

It was found that increasing the duration of decolorization to 120 min. allows to reduce the amount of hydrogen peroxide to 0.7% (**Table 11.7**). It is possible to recommend these conditions for use in industry. The value of the peroxide value of lecithin after treatment with hydrogen peroxide under these conditions was 45 mmol1/2O/kg. After their destruction by the enzyme superoxide dismutase – 6.8 mmol1/2O/kg.

Table 11.7 Determination of the effect of decolorization duration on the color of the lecithin

Amount of hydrogen peroxide (calculated as 100% peroxide)	Duration of discoloration, min.		
	90	120	180
	Color, mg of iodine		
0.5	12 ± 0.1	8 ± 0.2	6 ± 0.1
0.7	10 ± 0.2	4 ± 0.1	4 ± 0.2
1.0	6 ± 0.1	4 ± 0.1	4 ± 0.1

During the research, it was established that when sunflower lecithin is treated with hydrogen peroxide, it deodorizes the latter – the decolorized lecithin has a characteristic smell of oil and any other odors. When phospholipids are decolorized with concentrated hydrogen peroxide, hydroxyphospholipids are also formed, which are strong hydrophilic emulsifiers.

It is advisable to combine the obtained experimental data and propose a rational scheme for obtaining light, liquid, deodorized sunflower lecithins. The scheme is shown in **Fig. 11.4**.

It is proposed to introduce hydrogen peroxide and calcium salts into the wet gum. As a result, the formation of dark-colored forms of phospholipids due to less viscosity of lecithin, which is formed during the drying process of wet gum, its other quality indicators are better. The number of peroxide compounds is significantly lower than the option of introducing hydrogen peroxide into the already dried lecithin (45 and 145 mmol1/2O/kg, respectively).

The stage of deodoration of lecithin (ethanol treatment) drives to the fractionation of lecithin with the formation of two valuable fractions in the industry – the one that mainly contains phosphatyletanolamine, phosphatidylserine, phosphatidylinositol, phosphatide acids (main in weight) and fractions containing phosphatidylcholine (**Table 11.3**).

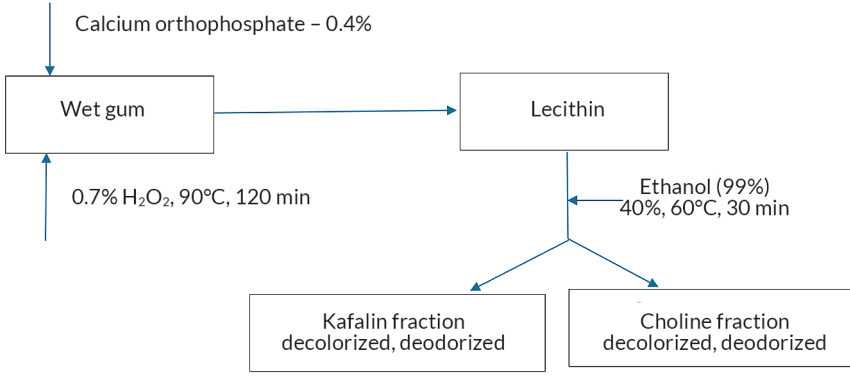


Fig. 11.4 The rational scheme for obtaining decolorized, liquid, deodorized sunflower lecithins

11.4 Conclusions

As a research result, it was proven that it is possible to get rid of the main technological disadvantages of sunflower phospholipids – intense taste and smell, dark color, high viscosity with the transition to a plastic non-liquid state.

Deodorization of sunflower lecithin is possible by dissolving it in ethyl alcohol in an amount of ≥ 40% relative to lecithin. In this case, such characteristics of the smell and taste of sunflower lecithin as fatty, sweet, nutty completely disappear. Caramel and floral taste and smell become barely noticeable. In this case, lecithin is fractionated into alcohol-soluble and alcohol-insoluble fractions. The separation

of the alcohol-soluble fraction can be significantly reduced (from 23 to 13% relative to lecithin) by using absolute ethanol. The quality indicators of the alcohol-insoluble fraction (main) meet the requirements for lecithins. The alcohol-soluble fraction (with a predominant content of phosphatidylcholine) will meet the requirements of the quality indicators after increasing the content of acetone-insoluble substances. It is advisable to carry out the treatment with acetone in one stage at a ratio of alcohol-soluble fraction: acetone as 1:1, the content of phospholipids in the fraction as a result becomes more than 60%.

It has been proven that under the condition of introducing certain diluents, it is possible to achieve a state when sunflower lecithin does not form a plastic consistency and is liquid throughout the shelf life. It has been proven that diluents should be introduced into the wet gum before its drying. In this case, the amount of diluents required to obtain a stably liquid lecithin is approximately halved. The effective concentrations of lipids, the addition of which to the sunflower wet gum leads to lecithin dilution to 12 Pa·s (at 25°C), i.e. to the value when lecithin does not plasticize during storage (the studies were conducted after 14 days of storage), namely: sunflower oil – 13%, oleic acid – 5%, oleic acid ethyl ester – 4%. However, such amounts of introduced lipids reduce the value of the indicator "insoluble in acetone" to a level lower than the requirements of the quality indicators, therefore their use in sunflower lecithins should be abandoned. According to the research results, the optimal diluents are calcium salts. The effective amounts of their presence for obtaining liquid lecithin are the following: calcium acetate – 0.4%, calcium orthophosphate – 0.4%, calcium chloride – 0.35%.

Rational conditions for sunflower lecithin decolorization were determined: the amount of hydrogen peroxide (in terms of 100% peroxide) – 0.7%; process temperature – 90°C; duration of decolorization – 120 min. Under such conditions, the color number of sunflower lecithin decreases from 18 mgJ_2/100cm^3 to 4–6 mgJ_2/100cm^3. Effective destruction of peroxide compounds formed during lecithin decolorization was carried out by the enzyme superoxide dismutase.

In order to determine the influence of different groups of phospholipids on lecithin darkening, its fractionation was carried out. It was proved that phospholipids, according to the degree of change in their color after heat treatment, create the following series (in descending order): phosphatidylcholines – phosphatidylinositols – phosphatidylserines and phosphatidylethanolamines. That is, the darkening of lecithin at elevated temperatures is primarily influenced by the phosphatidylcholine fraction. It has also been proven that there is no correlation between the sugar content in phospholipid fractions and their darkening as a result of heat treatment.

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CHAPTER 12

Use of asparagus waste to fortify bakery products

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Abstract

The modern industry of food production faces constant challenges, raised by growth of population, global environmental changes and high impact of geopolitical factors on the food supply chains. Sustainability in processes of food production and distribution is crucial for food security and rational management of valuable natural resources. High losses, especially in perishable crops like asparagus (up to 50% of the total production), are serious issue, which demands development of new approaches to reduce and rationally utilize the waste.

Asparagus is a highly valuable and popular vegetable crop. However, it rapidly loses its commercial quality due to the high level of metabolism in the spears, which contributes to significant product losses during processing and storage. Up to 20% of spears are additionally wasted due to the trimming during the storage, which contributes significantly to the production losses.

The chapter of the monograph is dedicated to the possibility of utilization of waste from asparagus processing for enriching food products, namely bakery products. The basal parts of asparagus spears, which are usually utilized, were proven to contain high amount of the phenolic compounds. The elemental analysis of the freeze-dried asparagus powder showed presence of many valuable microelements and high quantities of protein, which make such powder a valuable dietary supplement. A series of bread recipes in which part of the flour was replaced with the obtained asparagus powder was tested to produce bakery products with enhanced biological value. Four types of low-carbohydrate flours were tested (whole-grain spelt and quinoa, flaxseed, and amaranth), to which asparagus powder was added in various proportions. The bread produced using these new recipes was evaluated based on its physicochemical characteristics and organoleptic properties. It was shown that

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adding asparagus powder (5–10%) to amaranth, quinoa and flaxseed flour helped retain the shape of produced bread, reduced crumb moisture and facilitated uniform porosity, though did not provide positive impact on the organoleptic properties. At the same time, bread made with whole-grain spelt flour and up to 10% replacement with asparagus powder met all requirements for each of the indicators. These experimental results thus justify the replacement of up to 10% of spelt flour with asparagus powder to enhance the nutritional value of the product.

The use of asparagus powder in the bakery, therefore, allows for the reduction of food waste, the enhancement of product nutritional value through the inclusion of micronutrients, proteins, and antioxidants, and the expansion of the range of bakery products, including options for consumers with low-carbohydrate or gluten-free dietary needs.

Keywords

Asparagus, storage waste, vegetable powder, bread, food product enrichment.

12.1 Introduction

In the face of challenges currently confronting humanity due to global environmental changes and disruptions to established food supply chains caused by geopolitical factors, the importance of optimizing models of consumption and production cannot be overstated. Pursuit of active development of sustainable food production and rationalization of all processes in its chain is reflected, e.g. in Goal 12.3 of the United Nations Sustainable Development Goals for 2030, which aims to halve per capita food waste and reduce food losses along supply chains [1].

In modern supply systems, food losses still occur at all stages, from cultivation and storage to processing and consumption. The dominance in the structure of these losses is firmly held by fruit and vegetable waste. Although the global trend of increasing fruit and vegetable consumption has boosted their production over the last decade, annual losses of these products still reach 40 to 50% of the total harvest. Such high amounts of wasted material results in financial losses for all participants in the supply chain, from producers to consumers, as well as irreversible and wasteful losses of natural resources used during production. Therefore, rationalizing the processes of storage and transportation of plant-based products as well as development of strategies of smart utilization of wasted material, are extremely important for creating stable food systems and ensuring food security.

High losses during the storage of fruits and vegetables are caused by their low resistance to mechanical damage, high moisture content (75–95%), intense gas

exchange, and active post-harvest metabolism. In the case of Asparagus, a plant with high metabolic activity, waste can account for up to 50% of the total amount [2].

Asparagus (*Asparagus officinalis L.*) is one of the most popular vegetable crops in the world due to its taste, nutritional value, and high content of valuable phytonutrients. Thanks to the rapid growth in demand over the past 35 years, asparagus production worldwide has increased 5.5 times, and in Europe, it has doubled. In Ukraine, asparagus has traditionally been used rather as an ornamental plant, however, with the growing trend of healthy diets and the globalization of culinary preferences, it becomes popular among Ukrainians, stimulating farmers' interest in cultivating it.

Asparagus owes its global popularity to its valuable dietary properties and the presence of diverse biologically active substances [3]. It contains phenolic compounds, tannins, flavonoids (e.g., rutin, kaempferol, quercetin), anthocyanins, steroidal saponins, dietary fibers, carotenoids, chlorophylls, and sterols [4]. These compounds influence metabolic and regulatory processes, contributing to asparagus's pharmacological effects, such as antioxidant, antitumor, antidiabetic, hypoglycemic, hypolipidemic, antiepileptic, and immunomodulatory activities [3]. Asparagus proteins provide majority of essential amino acids, with asparagine and glutamine dominating, accounting for 40–43% of total amino acids, and exceeding the relative content found in animal-based products [5]. The spears are also rich in vitamins, including folic acid, phylloquinone, and tocopherol. Additionally, asparagus contains high levels of minerals such as potassium, calcium, and iron [3]. Introducing into diets products with high amounts of biologically active substances and phytonutrients, such as asparagus, may help to combat so-called "hidden hunger" – multiple micronutrient deficiencies caused by consuming an energy-dense, but nutrient-poor diet [6, 7].

Asparagus is primarily consumed fresh, but processed products, including canned and frozen asparagus, are also in demand, especially in Asian markets, where they are more traditional. Due to the high nutritional value and health benefits of asparagus, there is ongoing research to develop new products based on asparagus that retain the maximum amount of biologically active substances for market introduction [8, 9]. For example, in recent years, methods for freezing asparagus with pre-blanching, canning, and producing juices, teas, wines, vinegar, yogurt, and other fermented products, as well as recipes for pasta made from dried asparagus, have been patented in China [3]. Powders made by drying asparagus spears are used as food additives due to their high content of dietary fiber and biologically active substances [2, 3]. Extracts, powders, and juices from asparagus are widely used not only in food applications but also in medicine, cosmetology, and plant tissue culture. To utilize asparagus production waste, technologies are being developed for extracting enzymes, certain biologically active substances, and even producing cellulose nanocrystals [3, 10, 11].

The asparagus growing season in Ukraine is fairly short – from the last decade of April to early June. The edible part consists of young asparagus spears measuring 15–22 cm in length and up to 2 cm in thickness. These are the young parts of the plant with a high level of respiratory metabolism, and the respiration rate increases immediately after harvest due to wound stress [12]. Consequently, harvested asparagus spoils quickly: the shelf life of cut spears is 3–5 days at room temperature and 14–15 days when stored in a refrigerator [13]. Moreover, if canned, only the upper 15 cm of the asparagus spear is used, while the rest (up to 15–18 cm) is discarded as waste. At least 20% of edible asparagus parts are thus disposed during commercial processing, storage, and post-storage preparation. During preparation for storage or sale, initial processing of asparagus spears involves trimming the lower ends of the spears to create uniform bundles of standard height. The trimmed sections (usually about 2 cm) are classified as waste, furthermore, asparagus cuts are also refreshed after storage by additional trimming the dried portion to maintain the commercial appearance. Extending the shelf life of asparagus and reducing waste in the harvested products, can contribute to improving the availability of this valuable food product, enhancing nutritional diets, and reducing the burden on ecosystems.

Fruit and vegetable waste are often composted or used as organic fertilizer for soils, as well as for animal feed. At the same time, given the significant content of antioxidants, phenolic compounds, and other biologically active substances, asparagus waste represents a promising source of biologically active compounds and raw material for the creation of value-added products.

Our recent research, focused on the evaluation of asparagus processing waste as raw material for obtaining phytonutrients, confirmed, that basal parts of spears of asparagus varieties, cultivated in Ukraine (namely, Rosalie and Prius), contain high quantities of phenolic compounds [14]. In the study, phenolic content was analyzed for the whole asparagus spears, waste that was generated during preparation for storage, whole spears after the storage period, and waste generated during preparation for sale after storage. Phenolic compounds are of particular value in asparagus processing waste, since they are natural antioxidants, valuable for tissue protection. According to our observations, in the basal parts of asparagus spears, which are considered waste, content of phenolic compounds is 20–27% lower, if compared to thus in whole spears. Nevertheless, the total phenolic content in such waste remains relatively high: 74.77 mg/100 g in the Prius variety and 67.73 mg/100 g in the Rosalie variety. Additionally, no significant differences in the basal parts of asparagus (classified as waste) were observed before and after storage [14]. Therefore, asparagus waste from both studied varieties, Prius and Rosalie, can serve as a good source for obtaining polyphenolic compounds.

In addition to biologically active substances of phenolic nature, asparagus spears (including their basal parts) can also serve as a source of other valuable compounds, such as fiber, proteins and microelements. According to literature, the powder obtained by drying asparagus retains most of the heat-stable components and is therefore considered a promising food additive [10, 11]. The possibility of using it as an additive in various food products is currently the subject of active research [2, 3]. In this chapter, let's investigate the potential of asparagus-derived powder as an additive to the bread and bakery products. It is important to note, that such an additive can be obtained from otherwise wasted material during the asparagus harvesting stage without additional investments in crop cultivation, which highlights the cost-effectiveness of the approach.

Currently, the demand for bread is shaped by various target consumer groups. While some consumers are primarily guided by the cost and organoleptic properties of the product, other categories are increasingly focused on healthy eating and choose bakery products based on their high nutritional qualities, including dietary, taste, and aesthetic characteristics. Responding to these trends and aiming to attract specific audiences, manufacturers are experimenting with innovative recipes, particularly by adding functional ingredients.

The biological value of bakery products is often enhanced by incorporating alternative flours into the dough recipe instead of wheat flour [15]. For example, spelt flour (a species of wheat) has a high protein content (about 14–15%), which is comparable to that of wheat, but it is also rich in B vitamins, magnesium, iron, and fiber, and is better digested than regular wheat flour [16]. Spelt flour has a reduced gluten content but is not suitable for people with celiac disease due to its presence. Spelt flour is well-suited for baking bread, cookies, and pies, although it may be less elastic. Flaxseed flour has a very high fiber and omega-3 fatty acid content but low carbohydrate content, making it ideal for low-carb diets. It is also rich in lignans, antioxidants, and protein (about 35%), but due to its low starch content, it does not form dough structure and can only be used as an additive to other flours (10–20%) [17].

Amaranth flour also has a relatively high protein content, is rich in the essential amino acid lysine, as well as iron, magnesium, calcium, and B vitamins. It is suitable for gluten-free diets [18], but it has a strong, specific taste that can dominate and does not hold dough structure well [19]. Quinoa flour is also high in protein (similar to amaranth flour, with a protein content of about 14–15%), contains all essential amino acids, and is rich in fiber, antioxidants, B vitamins, and minerals (magnesium, zinc). It is gluten-free, but if improperly processed, it can have a bitter taste. Due to the absence of gluten, the structures of amaranth and quinoa flours are weak, making them suitable for cookies and pancakes, but they must be mixed with other flours for

bread production [20]. Compared to wheat flour, the described types of flour contain more protein (significantly more in the case of flaxseed flour) and fewer carbohydrates [15, 20]. Due to the lower gluten content or its absence, as well as insufficient starch content, these flours cannot fully replace wheat flour in bakery products and must be combined to achieve the proper dough structure [20].

Adding asparagus powder to such alternative flours, according to our assumptions, can partially compensate for the lack of gluten due to its rich protein composition. This could positively influence achieving the necessary parameters for bread baking while also enriching the bakery product with microelements, proteins, and biologically active substances. Such enrichment could be particularly valuable for consumers requiring gluten-free and low-carbohydrate diets.

12.2 Methods of research

The studies included were conducted with asparagus spears of the Prius and Rosali varieties, harvested in accordance with the requirements of CODEX STAN 225-2001 [21]. The basal parts of asparagus spears were freeze-dried to produce a powder. The raw material was pre-frozen at a temperature of –40°C. After the freezing phase was completed, the samples were placed in the chamber of a freeze dryer (model: CC-02, Sublimat, Ukraine). Drying was carried out at a chamber pressure of 15 Pa. The process consisted of two main stages. Primary drying, aimed at removing unbound moisture at a temperature of +5°C for 15 hours. Final drying, performed at +40°C for 20 hours. After the drying process was completed, the samples were ground into a fine powder using a laboratory mill (MILLER-800) and sieved through a mesh with pore size $\leq 200\ \mu$m. The resulting powder was stored in airtight containers at +4°C until further use in experiments.

12.2.1 Chemical analysis

Quantitative chemical analysis of the powder was conducted at the Sector for Microelement Studies of the State Institution "Institute for Occupational Health of the NAMS of Ukraine".

A 0.2 g sample of dried asparagus was dissolved in 3.0 ml of 65% nitric acid and autoclaved for 30 minutes, followed by mineralization in a MARS-One microwave oven for 25 minutes. After cooling, the sample volume was adjusted to 10.0 ml with deionized water. Macro- and microelement content was determined using inductively

coupled plasma optical emission spectroscopy (ICP-OES) on an "Optima 2100 DV" device (Perkin-Elmer, USA). Data processing was performed using the WinLab32 software for ICP-OES and statistical analysis in Microsoft Excel. Protein content in the dry sample was calculated based on nitrogen levels.

12.2.2 Laboratory baking of bread with asparagus powder

The laboratory baking of bread products with asparagus powder was conducted in the laboratory of the Department of Food Technologies at Uman National University of Horticulture.

The asparagus powder was incorporated into bread formulations for laboratory baking. Initial experiments evaluated the effect of adding 5% and 10% asparagus powder (**Fig. 12.1**) to bread mixtures made from whole-grain spelt, quinoa, amaranth, or flaxseed flour. Bread without asparagus powder served as the control. Fermentation, dough proofing, and baking conditions were optimized experimentally.

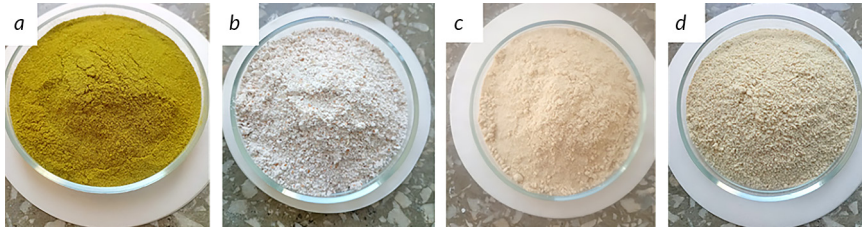

Fig. 12.1 Ingredients for the experiment: *a* – asparagus powder; *b* – whole-grain spelt flour; *c* – quinoa flour; *d* – flaxseed flour

Further studies focused on spelt flour mixtures, which yielded satisfactory results. Mixtures of asparagus powder and spelt flour were prepared in ratios of 0:100, 5:95, 10:90, 15:85, 20:80, and 30:70. The dough formulation was calculated based on 100 g of dry mixture, consisting of wholegrain spelt wheat flour and asparagus powder in a ratio of 95:5.

The formulation included the following ingredients (g):

– wholegrain spelt wheat flour – 95;
– asparagus powder – 5;
– sunflower oil – 1.5;
– table salt – 1.5;
– compressed baker's yeast – 1.5;

– sugar – 1.5;
– water – 50–55.

The dough fermented at 28–32°C for 150–180 minutes, was shaped, proofed, and baked in a steam-injected oven at 200–220°C for 15–20 minutes.

Bread was evaluated 16 hours post-baking using a previously established methodology [22]. For evaluation, next parameters were used: organoleptic properties (appearance, crust color, crumb elasticity, pore structure, taste, aroma), assessed by the group of experts, and physicochemical parameters (baking loss, specific volume, porosity, moisture, acidity). Moisture was measured with an SESh-3M device, and bread volume was determined by grain displacement using an RZ-BIO device, expressed in cm^3/kg of flour.

12.3 Results and discussion

12.3.1 Asparagus powder as a source of nutrients

Quantitative chemical analysis of the powder revealed a high content of micronutrients, in the powder obtained from the basal parts of asparagus (**Table 12.1**). The rich elemental composition of such powder allows for its potential use in enriching other products with biologically active substances.

Table 12.1 Content of chemical elements in dried asparagus

Element	λ, nm	C, (mg/kg)	Technical error, %	Detection limit, mg/kg
Mg	279.1	2564.5 ± 15.4	0.87	0.005
K	766.5	47591.7 ± 245.0	0.44	1.40
Ca	317.9	5635.6 ± 9.8	0.24	0.42
Mn	257.6	41.4 ± 0.3	0.65	0.005
Zn	206.2	110.5 ± 3.1	2.31	0.056
Fe	259.9	79.52 ± 2.5	3.12	0.042
Cu	324.7	8.71 ± 0.38	3.80	0.042
P	213.8	7317.3 ± 204.4	2.85	1.40
S	190.0	24093.87 ± 333.2	2.34	0.56

The detected microelements are essential for hematopoiesis, functioning of the nervous system and muscles, strengthening bone and cartilage tissue, supporting immunity, and regulating metabolism. The content of iron (Fe), magnesium (Mg),

phosphorus (P), zinc (Zn), and manganese (Mn) in dried asparagus is twice as high as in whole-grain wheat flour, while the copper (Cu) content is at least four times higher. The asparagus powder is particularly rich in potassium (K), importance of which importance cannot be overstated when it comes to reducing the risks and severity of cardiovascular diseases, maintaining muscle tone, and regulating water-salt balance.

The protein content in asparagus powder was also high, amounting to 5.14 ± 0.11% of the total powder mass. Adding it to food products, therefore, evidently contributes to a significant increase in their nutritional value due to the proteins, which also include essential amino acids. The high protein content, as well as the significant amounts of dietary fiber, pectins, and sugars in asparagus powder, are also noted in the literature, supporting our justification of using asparagus powder as an additive in various food products.

12.3.2 Evaluation of the feasibility of adding asparagus powder to bread recipes

To develop methods for laboratory baking of bread enriched with asparagus powder, let's experimentally determine the feasibility of replacing part of the flour in the recipe with asparagus powder. The amount of asparagus powder added to the dough was selected in a range of 5–30%, considering the requirements of the bread-making technological process. The bread was then baked, and its properties were compared with control samples baked from the corresponding flour without the addition of asparagus powder.

Bread made from whole-grain amaranth flour was characterized by a smooth surface without cracks or ruptures; the crumb quickly regained its original shape, retained moisture, and remained slightly sticky to the touch. It had developed porosity without hardening. The crumb color in all variants was brown, and the taste and smell were characteristic of this type of bread, without any off-flavors or odors. Adding asparagus powder to the bread reduced the crumb moisture, increased the uniformity of porosity, and decreased pore size (**Fig. 12.2**).

When 5% asparagus powder was added to whole-grain amaranth flour, the water absorption capacity of the dough did not change significantly. However, with an increase in the amount of powder to 10%, the dough's ability to retain moisture decreased (**Table 12.2**). Significant baking loss was observed even with the addition of 5% asparagus powder, with a value of 29.6%, which is 17% less than the control. The specific volume of the control amaranth bread was 1.08 cm^3/g, while the addition

of 5% vegetable powder reduced it by 5.5%. However, the addition of 10% powder increased the specific volume of the bread to 1.19 cm^3/g.

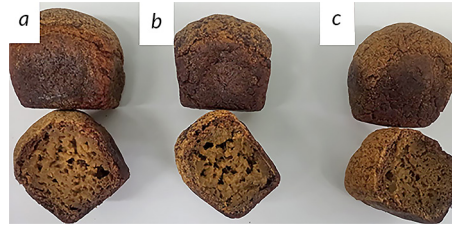

Fig. 12.2 Whole-grain amaranth flour bread: *a* – control; *b* – with addition of 5% asparagus powder; *c* – with addition of 10% asparagus powder

Table 12.2 Physicochemical indicators of bread made from whole-grain amaranth flour (control) and new recipes with the addition of asparagus powder

Indicator	Bread from whole-grain amaranth flour			
	Control	5% asparagus powder	10% asparagus powder	$LCD_{0.05}$
Specific volume of bread, cm^3/g	1.08	1.02	1.19	0.06
Baking loss, %	35.6	29.6	30.7	1.59

Bread made from defatted flaxseed flour had a smooth surface without large cracks or ruptures but was characterized by a high crumb density due to significant baking loss. The crumb regained its original shape but retained moisture, remaining slightly sticky to the touch, with low porosity and no hardening. When asparagus powder was added to defatted flaxseed flour, the crumb cracked after baking (**Fig. 12.3**).

The crumb color in all variants was dark brown, and the taste and smell were characteristic of this type of bread, without any off-flavors or odors. As shown in **Table 12.3**, increasing the amount of added asparagus powder to defatted flaxseed flour reduced the dough's water absorption capacity, significantly decreased the baking loss, and lowered the specific volume of the bread. For example, the highest percentage of baking loss was observed in the control sample, with a value of 34.1%, while the addition of 5% and 10% asparagus powder reduced this by 9–10%. The specific volume of bread made from flaxseed flour was 1.12 cm^3/g, and with the addition of 5% and 10% asparagus powder, it decreased by 2% and 9%, respectively. Thus, the addition of 10% asparagus powder to flaxseed flour had a significant impact on the specific volume of the bread.

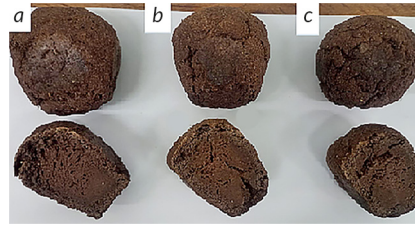

Fig. 12.3 Flaxseed flour bread: *a* – control; *b* – with addition of 5% asparagus powder; *c* – with addition of 10% asparagus powder

Table 12.3 Physicochemical indicators of bread made from defatted flaxseed flour (control) and new recipes with the addition of asparagus powder

Indicator	Bread from whole-grain amaranth flour			
	Control	5% asparagus powder	10% asparagus powder	$LCD_{0.05}$
Specific volume of bread, cm^3/g	1.12	1.10	1.02	0.05
Baking loss, %	34.1	31.1	30.7	1.9

Bread made from whole-grain quinoa flour was characterized by a smooth surface without cracks or ruptures. The crumb was dry to the touch, without hardening, and had low but uniform porosity, with small pore sizes. The crumb color in all variants was brown, and the taste and smell were characteristic of this type of bread, without any off-flavors or odors. Adding asparagus powder to the bread increased the crumb density, likely due to the significant baking loss. The pore size also decreased as the proportion of asparagus powder in the dough increased (**Fig. 12.4**).

From the data in **Table 12.4**, it is evident that adding asparagus powder to whole-grain quinoa flour significantly increases the baking loss of the bread. In the control sample, the value is 11.2%, while in the samples with 5% and 10% additions, it is 2.3 and 2.6 times higher, respectively.

Thus, unlike bread made from flaxseed flour, a positive effect of adding asparagus powder was observed in the recipe for bread made from quinoa flour, due to an increase in the dough's water absorption capacity and a significant increase in the bread's specific volume. In the control sample, this qualitative indicator of bread was 0.92 cm^3/g, while in the samples with 5% and 10% asparagus powder, it was 5% and 7% higher, respectively.

Despite some improvement in the physicochemical indicators of bread in the new recipes using asparagus powder compared to the respective control samples,

their overall organoleptic evaluations remained average, which may complicate the introduction of the tested recipes to the consumer market.

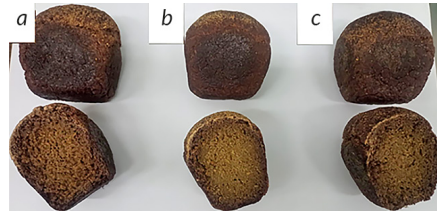

Fig. 12.4 Whole-grain quinoa flour bread: *a* – control; *b* – with addition of 5% asparagus powder; *c* – with addition of 10% asparagus powder

Table 12.4 Physicochemical indicators of bread made from whole-grain quinoa flour (control) and new recipes with the addition of asparagus powder

Indicator	Bread from whole-grain quinoa flour			
	Control	5% asparagus powder	10% asparagus powder	$LCD_{0.05}$
Specific volume of bread, cm^3/g	0.92	0.97	1.10	0.05
Baking loss, %	11.2	25.4	29.3	1.09

Fundamentally different results were obtained in the bread samples with the addition of asparagus powder to whole-grain spelt flour, which, based on our data, may have significant potential as a new bakery product. These bread samples were distinguished by better structure and appearance (**Fig. 12.5**), and therefore, to determine the optimal recipes, more variants were tested, and a broader range of quality indicators was used.

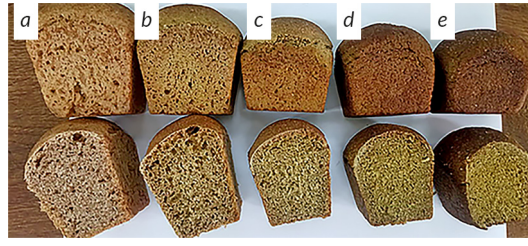

Fig. 12.5 Whole-grain spelt flour bread: *a* – control; *b* – with addition of 5% asparagus powder; *c* – with addition of 10% asparagus powder; *d* – with addition of 20% asparagus powder; *e* – with addition of 30% asparagus powder

12.3.3 Organoleptic and physicochemical indicators of bread made from whole-grain spelt flour with asparagus powder

Laboratory bread, in which a certain amount of asparagus powder was introduced with a proportional reduction in the amount of whole-grain spelt flour, was evaluated based on several organoleptic indicators (color, taste, smell) and physicochemical quality indicators. Additionally, its culinary properties (specific volume, porosity, moisture, acidity, and baking loss) were assessed. To determine the optimal recipes for laboratory baking, various proportions of asparagus powder and whole-grain spelt flour (hereafter referred to as "spelt flour") were tested. The samples contained 0%, 5%, 10%, 20%, or 30% asparagus powder in the mixtures, respectively.

According to the organoleptic indicators, bread made from whole-grain spelt flour met the established requirements: the surface was smooth, without large cracks or ruptures; the crumb was elastic, quickly regained its original shape, well-baked, not moist to the touch, not sticky, with developed and uniform porosity, and without hardening. The crumb color had a gray-yellow tint, and the taste and smell were characteristic of this type of bread, without any off-flavors or odors.

Table 12.5 presents the organoleptic quality indicators of bread made from spelt flour with the addition of asparagus powder in various proportions.

Bread made with the new recipes differed slightly in quality from the control sample: the crumb color was dark yellow, greenish-yellow, or greenish; the taste and smell were characteristic of asparagus. The asparagus powder contained anthocyanin pigments and had a pronounced green color.

It has been established that adding 5–10% asparagus powder to spelt flour dough is appropriate. Such bread had a uniformly colored (dark yellow) crust without ruptures or cracks, an elastic crumb (dark yellow, greenish-yellow), thin-walled porosity, a pronounced bread flavor, and a pleasant aroma of the additive.

The crumb of bread made with spelt flour and the addition of 20% and 30% asparagus powder had a greenish tint and a strongly pronounced taste and aroma of the additive, which could significantly affect consumer satisfaction. The overall sensory evaluation of the bread, based on a 9-point scale across nine characteristics, was also the highest for samples baked from mixtures containing 5–10% asparagus powder (**Table 12.6**).

All bread samples were rated 9 points for cust color and 8 points for crust surface. The glossiness of the crust in the control sample was rated 9 points, while the other bread variants scored just one point lower.

Table 12.5 Physicochemical indicators of bread made from whole-grain spelt flour (control) and new recipes with the addition of asparagus powder

Indicator	Content of asparagus powder in the baking mixture				
	0% (Control)	5%	10%	20%	30%
Appearance of the surface	surface smooth, without contaminations, cracks or ruptures			surface smooth, without contaminations, large cracks or ruptures	
Color of the surface	white-yellow	light yellow	yellow	brown	brown
Crumb appearance	Elastic, restores its original shape, baked through, not moist to the touch, not sticky, without hardening				
	with uniform porosity	with developed and uniform porosity	with uniform porosity	with not uniform porosity	
Color of the crumb	grey-yellow	dark-yellow	yellow, slightly green	greenish, particles of the enriching additive are visible	
Odor	characteristic for this type of bread			bready with a strong aroma of the additive	the aroma of the additive dominates
	without foreign odors	with the aroma of the additive			
Taste	characteristic for this type of bread			–	–
	without foreign taste	with a hint of the additive			with a strong taste of the additive

Table 12.6 Quality of bread made from whole-wheat spelt flour (control) and new recipes with the addition of asparagus powder

Indicator		Content of asparagus powder in the baking mixture				
		0% (Control)	5%	10%	20%	30%
Crust surface		8	8	8	8	8
Crust color		9	9	9	9	9
Glossiness of the surface		9	8	8	8	8
Crumb color		7	7	7	4	4
Crumb elasticity		7	8	7	4	4
Aroma		8	8	7	7	7
Taste		7	8	7	4	4
Crumb consistency during chewing		7	8	7	4	4
Pore size		8	9	5	3	1
Uniformity of pore distribution		9	7	8	8	8
Overall	score	8.8	8.9	8.1	6.5	6.3
	%	97	99	90	73	70

Bread with the addition of 5% vegetable powder was rated 8 points for crumb elasticity, crumb consistency during chewing, taste, and aroma, which is one point higher than the control sample and bread with 10% asparagus powder. The crumb condition and taste of the bread with 20% and 30% powder were rated 4 points, while the aroma of this bread received 7 points.

The bread samples differed in crumb pore size. The best pore size was observed in the sample with 5% powder and the control, which scored 9 and 8 points, respectively. As the amount of powder in the bread increased, a significant reduction in pore size was observed. However, all bread samples were characterized by high uniformity of pore distribution, scoring between 7 and 9 points.

The overall quality assessment of the bread studied was very high for three samples: the control and those made with spelt flour mixed with 5% and 10% asparagus powder, scoring 8.1–8.9 points or 90–99% of the maximum value. Lower scores were obtained for bread samples with 20% and 30% vegetable powder added to the dough recipe, scoring 7.6–7.8 points or 70–73%, which is significantly lower than the standard but still a fairly high value.

As shown in **Fig. 12.6**, during baking, the bread sample with 5% asparagus powder outperformed the control in terms of volume increase, as the use of the additive intensifies the dough fermentation process. This is likely explained by the introduction of sugars and organic acids to the dough due to the addition of asparagus powder. These substances serve as a nutrient medium, participate in the biosynthesis of cellular metabolic components, and perform various functions in the metabolism of yeast cells.

Fig. 12.6 Bread samples during baking (from left to right): whole-grain spelt flour bread control, and bread with addition of 5%, 10%, 20%, 30% asparagus powder, respectively

A higher quantitative increase (10–30%) in the amount of asparagus powder in the dough negatively affected the gluten properties of spelt flour, leading to a reduction in the dough framework. However, significant baking loss was observed only

with the addition of 30% vegetable powder to the dough recipe made from whole-grain spelt flour, where the baking loss amounted to 16.8%, which is only 8% higher than the control.

The specific volume and porosity of the control bread sample were 2.40 cm^3/g and 68%, respectively. When 5% asparagus powder was used, these indicators were almost identical to the control sample, amounting to 2.38 cm^3/g and 67%, respectively. In other samples, these indicators were lower than the control by 9–19% and 6–11%, respectively (**Table 12.7**).

Table 12.7 Physicochemical indicators of bread made from whole-wheat spelt flour (control) and new recipes with the addition of asparagus powder

Indicator	Content of asparagus powder in the baking mixture					$LSD_{0.05}$
	Control	5%	10%	20%	30%	
Moisture, %	44.2	44.8	45.6	45.4	46.0	2.26
Acidity, degree	3.7	3.9	4.0	4.1	4.1	0.20
Porosity, %	68	67	62	57	55	3.4
Specific volume of bread, cm^3/g	2.40	2.38	2.26	2.18	2.14	0.11
Baking loss, %	15.4	15.6	16.2	16.1	16.8	0.80

A decrease in the specific volume of experimental samples with the addition of vegetable powder to the dough recipe in amounts of 10–30% is associated with a significant reduction in bread porosity. In the studied samples, an increase in acidity by 5–10% was determined compared to the control samples. The more intensive acid accumulation in the dough samples of the new recipes is due to the content of organic acids in the raw material. This may be related to the intensification of lactic acid fermentation, which indicates the creation of more favorable conditions for lactic acid bacteria.

Thus, based on the obtained results, the replacement of part (5–10%) of the whole-grain spelt flour in the recipe with dried and ground asparagus during bread production has been experimentally substantiated and implemented. In the future, it is possible to determine the feasibility of using asparagus powder in the production of other food products.

12.4 Conclusions

In this chapter, the possibility of enrichment of bakery products via inclusion of asparagus powder into the dough was demonstrated. It was shown that dried

powder from the basal parts of asparagus contains a high amount of protein – about 5% of its mass – as well as significant amounts of microelements. Rich chemical composition and previously demonstrated high content of antioxidants, dietary fiber and other organic compounds, thus opens up possibilities for using asparagus powder as a food additive.

The efficient introduction of the asparagus powder into the baking mixtures was experimentally proven based on tests with bread, prepared from quinoa, amaranth and flaxseed flour. Adding asparagus powder (5–10%) to gluten-free flour bread formulations helped retain the bread's shape, reduced crumb moisture, and increased pore uniformity, but also led to more significant baking loss. Despite improvements in the physicochemical properties of bread with the new recipes, their overall organoleptic evaluations remained average.

Replacement of the portion (optimally 5–10%) of whole-grain spelt flour with the asparagus powder provided excellent results, allowing to preserve high bread quality and taste (90–99% of the maximum total score), while enhancing the product nutritional value. Developed recipes thus allow to expand the range of bakery products and can be recommended for the high-scale production. Noteworthy, asparagus powder can be produced from parts of asparagus spears, currently wasted during the post-harvest treatment, without introduction of complicated additional technological processes, allowing to more rationally utilize such valuable source of nutrients.

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CHAPTER 13

Innovative potential of sea buckthorn pectin in providing textural properties to food and pharmaceutical products

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Abstract

The innovative potential of sea buckthorn pectin in food structure formation has been demonstrated, attributed to its unique functional properties. This study presents the results of theoretical and experimental investigations into the characteristics of pectin extracted from the peel of Hippophae rhamnoides (cv. "Leikora") grown in the right-bank region of Kherson, Ukraine.

In food and pharmaceutical processing technologies, there is a growing need for viscous solutions with adjustable rheological properties, which depend on equipment specifications and the desired characteristics of the final product. To assess possible structural transitions, the influence of sea buckthorn pectin concentration on the activation parameters of viscous flow – namely, activation enthalpy and activation entropy – was examined.

The studied sea buckthorn pectin exhibited a notably low "critical" concentration, indicating a high thickening capacity. Within the studied concentration range, the activation enthalpy and entropy changed in parallel. As the polysaccharide concentration increased, both activation parameters initially increased and subsequently declined, while viscosity increased throughout the entire concentration interval. At sub-critical pectin concentrations, the effective shear viscosity was primarily governed by the activation enthalpy. In contrast, above the critical concentration, viscosity was mainly determined by the entropic component.

It was shown that aqueous solutions of sea buckthorn pectin can be effectively used as model fluids for simulating the complex rheological behavior of materials employed in various technological processes. The rheological properties of food

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systems incorporating sea buckthorn pectin were also investigated, and deformation parameters of experimental model formulations of combined meat-vegetable-pectin pastes were determined.

In samples containing sea buckthorn pectin, a decrease in total, plastic, and elastic deformation was observed. The results of rheological and physico-mechanical tests demonstrated that the incorporation of sea buckthorn pectin into the formulation significantly influenced the structural integrity of the composite mixtures. Experimental data confirmed that sea buckthorn pectin improved the stability and homogeneity of highly concentrated meat-plant systems, facilitating the formation of a cohesive and stable food matrix.

The influence of sea buckthorn pectin on the techno-functional properties of food and pharmaceutical systems holds promising potential for further research, especially in light of its innovative applications.

Keywords

Sea buckthorn pectin, innovation potential, rheological properties, activation enthalpy and entropy, mechanical stability, deformation parameters, food and pharmaceutical systems.

13.1 Introduction

Sea buckthorn pectin is typically classified as a low-methoxyl pectin, consisting of a mixture of linear and branched polymers of α-*D*-galacturonan and other polysaccharides. Its innovative potential for food structure formation is considerable due to its unique functional properties. Pectins, owing to their ability to modify solution behavior through thickening, emulsification, stabilization, encapsulation, flocculation, swelling, and gelation, are used across a wide range of industrial sectors, including food, chemical, pharmaceutical, cosmetic, textile, paint, ceramic, petroleum, ecological technologies, and medicine.

The core aspects of the innovative potential of sea buckthorn pectin include its thickening, gelling, and emulsifying capabilities; its use as a functional food ingredient; valorization of processing by-products; and expansion of product ranges. In the context of rising demand for natural and "clean-label" food ingredients, pectin extracted from sea buckthorn offers an appealing alternative to synthetic thickeners and stabilizers. It can be obtained from pomace and other sea buckthorn processing waste, contributing to sustainable raw material utilization and waste reduction. Moreover, it presents economic opportunities at the regional level by fostering local agriculture and food industry development.

The distinctive properties of sea buckthorn pectin open new possibilities for designing products with novel textures and enhanced functional attributes. Its application enables manufacturers to meet growing consumer demand for healthy, natural, and innovative food products. However, certain challenges must be considered. The properties of pectin vary significantly depending on the sea buckthorn variety, maturity stage, cultivation conditions, and extraction methods. This may lead to variability in the quality and functional performance of the final pectin, including its thickening capacity. The molecular weight and degree of branching of pectin molecules also influence their rheological behavior, such as viscosity and gel-forming ability. These parameters may differ depending on the raw material source and extraction process, complicating standardization of pectin properties.

Compared to traditional pectin sources, research into the functional properties and applications of sea buckthorn pectin remains limited, potentially hindering the development of optimal formulations and processing techniques. Currently, quality and functionality standards for sea buckthorn pectin are less clearly defined than for commercially available pectins, which may limit its industrial scalability.

Nonetheless, ongoing research into extraction, characterization, and application of sea buckthorn pectin remains active. Due to its functional relevance, the investigation of the rheological properties of sea buckthorn pectin is particularly timely. Rheological properties – such as viscosity, elasticity, flow, and gelation capacity – are crucial for understanding how sea buckthorn pectin behaves in various food matrices. Such data enable the definition of quality benchmarks for its use as an ingredient, ensuring production process stability and predictability of end-product characteristics.

Understanding rheological behavior supports the optimization of mixing, heating, cooling, and other technological operations involving pectin, thus enhancing production efficiency and product quality. In certain food applications or drug delivery systems, the rheological properties of pectin may impact the release rate of active compounds, making this an important area for development of controlled-release products. Furthermore, these studies contribute to a deeper understanding of pectin's molecular structure, gelation mechanisms, and molecular-level interactions with other components. Comparing the rheological characteristics of sea buckthorn pectin to pectins from other sources broadens scientific knowledge and informs its potential applications. Ultimately, such research is essential for optimizing the use of sea buckthorn pectin in food and pharmaceutical industries, expanding its applications, and developing higher-quality, health-promoting products.

Although pectin is generally a valuable polysaccharide in the food and pharmaceutical industries, research on sea buckthorn pectin is limited and its applicability

is not well characterized. Gaps exist in the understanding of the specific properties of pectin extracted from sea buckthorn peel. The potential of sea buckthorn pectin, although recognized for providing textural properties, requires deeper investigation of sea buckthorn peel pectin to optimize its use in various products. There are a number of unresolved issues regarding its application for shaping the texture of food products that require further research. Sea buckthorn pectin from different geographical regions or different varieties may have different chemical and physicochemical properties, so it is necessary to study in more depth how the structural features of sea buckthorn pectin, which grows in the south of Ukraine, affect its ability to form viscous systems, to obtain a thermodynamic understanding of the structural aspects of the processes occurring in solutions of this polysaccharide, to identify the features of its functional behavior in food and pharmaceutical matrices. Solving these issues will allow for more effective use of sea buckthorn pectin as a valuable, natural and functional ingredient for innovative food products and pharmaceuticals, which, in turn, will contribute to expanding the range of functional products and efficient use of resources.

Therefore, the research topic "Innovative potential of sea buckthorn pectin in providing textural properties to food and pharmaceutical products" is both timely and relevant.

The primary aim of this study is to provide scientific evidence and practical data that substantiate and expand the application potential of sea buckthorn pectin as a valuable, innovative, and functional ingredient. Specifically, the objective is to reveal the potential of sea buckthorn-derived pectin in enhancing the textural properties of food and pharmaceutical products.

The scientific novelty of the study "Innovative potential of sea buckthorn pectin in providing textural properties to food and pharmaceutical products" lies in its focus on an underexplored but promising source of pectin – sea buckthorn. The novelty is not limited to the identification of pectin within sea buckthorn, but extends to a detailed analysis of its textural properties. Analysis of the textural properties of sea buckthorn pectin opens up opportunities for innovative and effective use of this natural polymer in the food and pharmaceutical industries.

13.2 Justification of using sea buckthorn pectin feasibility as regulators of food and cosmeceutical products consistency

Pectin can be extracted from agricultural biomass and fruit and vegetable processing waste using various methods. Naturally, pectin exhibits physicochemical

properties suitable for applications in both food and pharmaceutical industries. Pectin is a complex polysaccharide found in plant cell walls and consists of galacturonic acid residues. Pectin can be extracted from agricultural biomass, fruit and vegetable processing waste by several methods. Naturally, pectin has characteristics that are considered for application in the food industry. These characteristics include gelling, thickening, emulsifying, food encapsulation, and food coating. Reference [1] provides a comprehensive review of the structure of pectin, various extraction methods, and its applications in the food industry. However, pectin obtained through conventional extraction may exhibit certain limitations that restrict its broader utilization. To address these challenges, the review also discusses several modification techniques aimed at enhancing the functional properties of natural pectin. As a natural biomolecule, pectin acts as a biological modifier and is widely utilized in biochemistry, nutrition, and medicine. Due to its safety, biological activity, and biodegradability, pectin has attracted significant scientific interest. Studies have shown that plant-derived pectin possesses antioxidant [2], antitumor [3], and prebiotic [4] properties. Its unique emulsifying and gelling properties also make it a valuable functional food additive [5].

In [6], pectins from citrus peels of common varieties from different growing regions in China were characterized, and their comparison was carried out in terms of basic structure, composition (Fourier transform IR spectra, molecular weight distribution, monosaccharide composition), and functional properties (thermal stability and rheological properties). The relationship between chemical structure and antioxidant activities *in vitro* of these CPPs were also investigated comprehensively. Among the 10 kinds of citrus peel pectins, Shatangju (CPP-6) and Xuecheng (CPP-7) own superior antioxidant biological activity and Dahongpao (CPP-3) and Buzhihuo (CPP-9) had excellent functional properties (thermal stability and viscosity). According to the correlation analysis, molecular weight, galacturonic acid content and degree of methyl-esterification were beneficial to increase the thermal stability and viscosity of citrus peel pectins, while the rhamnose content, rhamnogalacturonan I region and lower molecular weight can improve citrus peel pectins antioxidant activity. Findings suggest that CPP-6 and CPP-7 may be useful as a potential natural antioxidant in pharmaceutical and cosmetic industries. Meanwhile, CPP-3 has great application potential in high temperature food and CPP-9 can be used as a thickener or stabilizer in the food industry [6].

Recently, extracting pectin from plant by-products has gained traction due to its low toxicity and inherent bioactivity. Sea buckthorn peel, a by-product of processing, contains a notable amount of pectin. Pectin is a non-toxic, natural, and multifunctional heteropolysaccharide, and one of the primary components of plant

cell walls, comprising 0.5 to 4.0% of the total fresh weight of plant materials [7]. Chemically, pectin is composed mainly of D-galacturonic acid residues, along with L-rhamnose (Rha), D-galactose (Gal), L-arabinose (Ara), and up to 13 other monosaccharides [8].

Determining the structure of pectin is complex, as its composition is influenced by plant origin, extraction conditions, growing location, and environmental factors [9]. Additionally, pectin undergoes modifications during plant maturation, processing, isolation, and storage [10]. Its biological activity is dictated by the composition of constituent sugars and substituent groups, and their interactions can enhance pectin's functional properties [11].

The chemical composition and molecular architecture of pectin vary significantly depending on the plant tissue type and extraction method [12]. Present consensus defines pectin as a heterogeneous polysaccharide with four main structural domains: homogalacturonan (HG), xylogalacturonan (XGA), rhamnogalacturonan I (RG-I), and rhamnogalacturonan II (RG-II) [13]. Although their relative proportions differ, HG and RG-I are the predominant components. RG-I consists of a repeating disaccharide backbone of rhamnose and galacturonic acid, decorated with linear or branched arabinan and/or galactan side chains. RG-II features a conserved structure composed of a short HG segment substituted with complex side chains made up of thirteen different monosaccharides and over twenty glycosidic linkages [14].

Pectin molecules are structurally organized into alternating regions: smooth, unbranched HG domains and branched, flexible RG-I-rich "hairy" regions. The hairy regions display greater compositional and structural diversity than the smooth ones, containing a wide array of monosaccharides [15].

In one study, high-methoxyl sea buckthorn pectin (SBHMP) was extracted from sea buckthorn peel with a yield of 8%. The SBHMP had a degree of esterification of 57.75% and contained 65.35% uronic acids. Structural and morphological analyses using HPLC, FTIR, and SEM revealed that SBHMP had a sheet-like, layered morphology and was mainly composed of galacturonic acid, arabinose, galactose, rhamnose, and mannose, indicating predominance of HG and RG-I domains [16].

In recent years, increasing attention has been devoted to the rheological properties of food colloids due to their strong correlation with functional performance. Compared to other colloidal systems, pectin solutions exhibit Newtonian-like flow at low concentrations and pseudoplastic (shear-thinning) behavior at higher concentrations [17]. Pectin viscosity is not only determined by its structure but also by concentration, pH, and ionic strength [18]. Pectin obtained via ultrasound-assisted extraction under optimized conditions exhibited clear non-Newtonian shear-thinning behavior at concentrations between 1.5% and 3.0% [19].

Sea buckthorn peel is a by-product of sea buckthorn processing, rich in various bioactive compounds. In [20], sea buckthorn high methoxyl pectin (SBHMP) was extracted, yielding 8% of light-colored product. SBHMP was classified as high methoxyl pectin, with a degree of esterification of 57.75% and a uronic acid content of 65.35%. The structural and morphological characteristics of SBHMP were analyzed using high-performance liquid chromatography (HPLC), Fourier-transform infrared spectroscopy (FTIR), and scanning electron microscopy (SEM). The results indicated that SBHMP exhibited a sheet-like, layered, and stacked morphology. It was mainly composed of galacturonic acid, arabinose, galactose, rhamnose, and mannose, suggesting that the extracted polysaccharides were primarily of the homogalacturonan (HG) and rhamnogalacturonan-I (RG-I) types.

In addition, SBHMP demonstrated significant gelling, thickening, and emulsifying properties. The results showed that SBHMP could form jelly-like gels under acidic and high-sucrose conditions, exhibiting shear-thinning behavior and increasing apparent viscosity with higher concentrations of both pectin and sucrose. Furthermore, SBHMP was capable of forming oil-in-water emulsions at pectin concentrations ranging from 1.0% to 3.0%. At concentrations of 2.0% and 3.0%, the emulsions remained stable over a storage period of 7 days. The findings of this study highlight the potential of SBHMP as a food-grade thickener and emulsifier, supporting the value-added utilization of sea buckthorn processing by-products [20].

In recent years, studies have shown that extracts from sea buckthorn berries, leaves, and seeds possess a wide range of biological activities [21, 22]. With the advancement of the sea buckthorn industry, substantial amounts of pomace, peel, seed meal, and other by-products have been generated. However, these materials have not been fully utilized, resulting in considerable resource wastage.

Currently, the extraction of pectin from plant-based by-products has attracted considerable attention due to its low toxicity and beneficial biological activity. Previous research indicates that fruit and vegetable peels contain significant amounts of pectin, with notable variability in composition and functional characteristics depending on the plant source. However, studies focused specifically on sea buckthorn pectin remain limited, and its functional application properties are not yet well defined.

Moreover, the composition of bioactive compounds in sea buckthorn is known to vary depending on growing conditions. Notably, sea buckthorn cultivated in plateau regions tends to exhibit higher concentrations and enhanced functionality of bioactive components compared to those grown in plains [23]. Therefore, exploring the potential of plateau-grown sea buckthorn peel as a pectin source, and characterizing its functional properties, holds significant promise for the development of innovative food and nutraceutical products.

13.3 Research materials and methods

An alternative source was used to obtain pectin, namely sea buckthorn peel [24]. This by-product of sea buckthorn fruit processing contains a significant amount of biologically active compounds. To date, research on pectin derived from sea buckthorn remains limited, and its application characteristics are not yet well defined. Furthermore, the composition and function of bioactive components in sea buckthorn vary depending on the habitat, influencing both their concentration and biological activity.

The aim of this study was to extract pectin from sea buckthorn peel. The test samples included cultivated *Hippophae rhamnoides* of the "Leikora" variety and wild-growing sea buckthorn. Both samples were collected from the right bank of the Kherson region (Ukraine).

According to a previously described method [25, 26], the sea buckthorn peel was mixed with distilled water at a raw material-to-liquid ratio of 1:10 (w/v), with the addition of 0.5% citric acid, 0.5% sodium ascorbate, and 0.2% ethylenediaminetetraacetic acid (EDTA). The pH of the mixture was adjusted to 2.0 using 1 M HCl, followed by incubation at 80°C for 1 hour.

After incubation, the mixture was centrifuged at 6500 rpm for 15 minutes. The resulting supernatant was concentrated using rotary evaporation, and 0.0004% sodium metabisulfite was added for mild decolorization. The solution was then mixed with 1.5 volumes of ethanol and allowed to stand for 4 hours. Pectic polysaccharide was recovered by dialysis and lyophilization.

The optimal extraction conditions were: temperature of 70 ± 2°C, pH 2.5–3.0, and extraction time of 10–12 hours. Acidification was performed with sulfuric acid. The extraction process was accompanied by filtration.

To obtain low-methoxyl (LM) pectin, de-esterification was carried out in ethanol with the addition of either an acid or a base.

Pectin was precipitated from the filtrate/ethanol mixture (up to 96 vol. %) at a ratio of 70:30. The precipitate was separated by filtration, again using a canvas filter.

Drying. Pectin obtained from the filtrate was placed in plastic trays and dried in a drying oven at a constant temperature of 60°C for 48 hours to remove excess moisture.

After drying, the product was stored in an airtight container until further use. The final powder moisture content should not exceed 5% by weight.

The appearance of the obtained pectin is shown in **Fig. 13.1**.

The obtained extract contained a mixture of pectic substances with varying molecular weights and degrees of esterification.

The following ingredients were used in the study:

– chicken meat (DSTU 3143:2013 "Poultry meat. General technical specifications", with Amendment No. 1);

– beans (DSTU 8672:2016 "Edible beans. Technical specifications", effective from 01.10.2017);

– drinking water (DSTU 7525:2014 "Drinking water. Requirements and methods of quality control", effective from 01.02.2015).

Measurements of rheological parameters of pectin solutions and a model mixture of canned poultry with pectin were performed using a Brookfield Model DV-III rheometer (Brookfield, Great Britain) (**Fig. 13.2**).

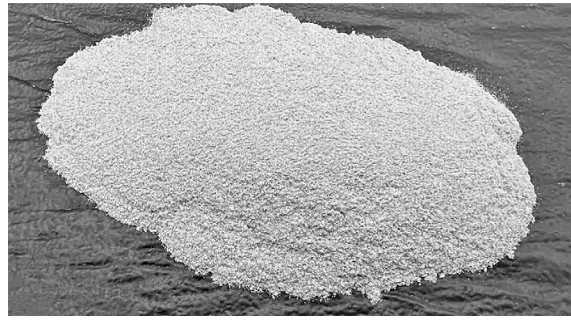

Fig. 13.1 Pectin obtained in the laboratory from sea buckthorn peel

Fig. 13.2 Brookfield Model DV-III rheometer

A sample of the tested solution weighing about 0.5 g was placed in the rheometer bowl under the spindle. Rheological parameters were measured when the spindle rotated at different shear rates, from low to high and back. During the studies, the solution samples were thermostated with an accuracy of ± 0.1°C using a Brookfield TC-350 thermostat (Brookfield, Great Britain) equipped with a flow cell (thermostat fluid – purified water). The results were used to construct rheograms showing the dependence of shear stress (τr) and dynamic viscosity (η) on the velocity gradient (Dr) in the range from 0 to 500 1/s.

The steady-state flow behavior of the prepared pectin solutions was measured at shear rates ranging from 0 to 500 s^{-1}. The effect of temperature on the flow behavior of pectin substances solutions at 0.5–2.5% (w/v) concentrations and pH 2.0–6.0 (prepared at a concentration of 1.0% (w/v)) was determined by measuring with a gradual temperature increase in the temperature range from 10 to 60°C at a heating rate of 10°C/min and an angular velocity of 0.1 rad/s.

The flow characteristics were determined using the Ostwald-de Waele rheological model, which describes plastic behavior or thickening under shear and is calculated by formula (13.1)

$$\tau = K \cdot \gamma^{n}, \tag{13.1}$$

where τ – shear stress (Pa); K – consistency index (Pa·s); γ – shear rate (s^{-1}); n – flow behavior index (dimensionless). In the investigated shear rate range, the viscosity of solutions was determined by formula (13.2)

$$\eta = \frac{P}{\gamma} = K\gamma^{n-1}. \tag{13.2}$$

The consistency index is relevant for the consistency of a liquid: if $n = 1$, the liquid is Newtonian, and the parameter K has the value of the Newtonian viscosity η. The flow behavior index is a deviation from Newtonian behavior. If $n < 1$, the viscosity decreases with increasing shear rate, which is characteristic of non-Newtonian plastic liquids [27–29] The mechanical stability (MS) of the samples was calculated as the ratio of the strength limit of the structure before fracture (τ_1) to the strength limit after fracture (τ_2) according to the formula (13.3)

$$MS = \tau_1 / \tau_2, \tag{13.3}$$

where τ_1 – the strength limit of the structure before failure; τ_2 – the strength limit of the structure after failure.

The value of the *MS* characterizes the degree of destruction of the structure of the samples in the process of irreversible deformation [30, 31].

To calculate the deformation characteristics, used the fundamental equation for elastic materials is Hooke's Law, which states

$$\sigma = E \cdot \varepsilon, \tag{13.4}$$

where σ – the stress; E – the modulus of elasticity; ε – the strain. For materials with elastoplastic behavior, more complex models such as the Prandtl-Reuss equations are used to describe stress-strain relationships during plastic deformation.

The Prandtl-Reuss equations consider both elastic and plastic strains

$$d\varepsilon = d\varepsilon_e + d\varepsilon_p, \tag{13.5}$$

where $d\varepsilon_e$ – the elastic component; $d\varepsilon_p$ – the plastic component of the strain [32].

All rheological behavior measurements were performed in triplicate and the values are presented as mean ± standard deviation ($n = 3$). The viscosity of the solutions was analyzed and statistically compared using the *t*-test.

13.4 Research results and discussion

13.4.1 Study of rheological properties of sea buckthorn pectin

In the practice of food and pharmaceutical technologies, there is a need to use viscous solutions with different viscosity values, which are determined by the characteristics of the equipment and the properties of the finished product. A necessary condition for creating an optimal recipe for a product with the required viscosity is the availability of data on the nature of the dependence of the system viscosity on the thickening agent concentration. There are several approaches to the graphical interpretation of the polymer solutions viscosity concentration dependence. The relationship between the solutions viscosity of almost any polysaccharide and its concentration is exponential. Representation of such a dependence in the "viscosity–concentration" coordinates clearly displays a sharp increase in viscosity with an increase in the concentration of the polysaccharide, but makes it difficult to assess some features of their rheological behavior. It was proposed to construct the concentration dependences of the viscosity of polymer solutions using the "viscosity-concentration" coordinates, which allows presenting these dependences

in linear form over a wide range of concentrations [33]. At the same time, in the area of moderately and highly concentrated solutions of polysaccharides, the use of semi-logarithmic coordinates seems to be the most preferable. The resulting simplification of the obtained dependencies does not prevent an objective assessment of the thickening capacity of various polysaccharides.

Fig. 13.3 shows the dependence of the viscosity of a sea buckthorn pectin solution on concentration at 25°C and a shear rate gradient of 500 s^{-1}.

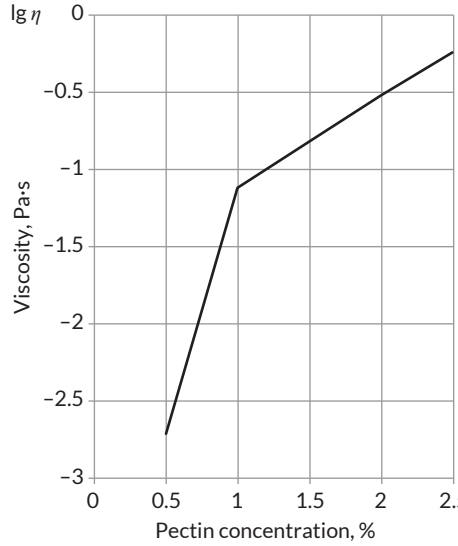

Fig. 13.3 Dependence of solution viscosity on the concentration of sea buckthorn pectin

The concentration dependence of viscosity in semi-logarithmic coordinates is expressed by two intersecting straight lines. The presence of an inflection point corresponds to a certain "critical" concentration. The presence of an inflection point on the viscosity concentration dependence is evidence that two straight-line sections of the dependence correspond to two different mechanisms of viscous flow.

To assess possible structural changes, the effect of the concentration of sea buckthorn pectin on the activation parameters of viscous flow of solutions was studied, since such indicators as heat and entropy of activation of viscous flow are very sensitive to the strength of the structure and its orderliness [34].

It is proposed to calculate the activation parameters based on the Frenkel-Eyring equation [35], which describes the temperature dependence of the viscosity

of a liquid from the standpoint of the theory of absolute reaction rates. However, during relatively large changes in temperature, the viscosity of the liquid begins to differ more and more from the values calculated by the Frenkel-Eyring formula. The real physical reason why the viscosity begins to differ from the values calculated by the Frenkel-Eyring formula during large temperature changes is that the temperature dependence of the activation free energy of viscous flow is not only in the form Gibbs energy of activation, but it can also be in a very complicated way due to the dependence of ΔH and ΔS on temperature: $\Delta G(T) = \Delta H(T) - T\Delta S(T)$.

If the structural temperature of the liquid has increased due to the influence of any substance, then when cooling that liquid, the temperature at which the viscosity is infinitely large will arrive sooner, that is, the liquid will be structured more quickly. From this point of view, it can be said that the increase in the structural temperature of the liquid due to the effect of any dissolved substance and other physical parameters means its structuring compared to the pure liquid as a result of this effect. Likewise, it can be said that the decrease in structure temperature is equivalent to the collapse of the structure of the liquid. Let's note that liquids with a structural temperature equal to zero, that is, the temperature dependence of viscosity can be expressed quite well by the Frenkel-Eyring formula, are called free liquids, and vice versa, liquids with a certain internal structure, that is, a non-zero structural temperature, are called non-free liquids [36].

In this work, the activation parameters were calculated using the following equation (13.6)

$$\Delta H - T\Delta S = 4 + 2.303RT\lg\eta. \quad (13.6)$$

The dependence of the heat and entropy of viscous flow activation of sea buckthorn pectin solutions on concentration at a shear rate of 500 s^{-1} and a temperature of 25°C is shown in **Fig. 13.4**.

The concentration dependence of the activation parameters has an extreme character. Both the heat and the entropy of the activation of the viscous flow reach their maximum in the region of the critical concentration of the solution, that is, at the same point where the viscosity change curve undergoes a break. With an increase in the concentration of sea buckthorn pectin in the interval up to the critical concentration, there is an increase in the number of macromolecules involved in the process of viscous flow, which is accompanied by an increase in the entropy of the system from 12.13 to 26.48 kJ/mol. As a result of the increase in the total number of macromolecules of the polysaccharide, the number of links between individual segments of macromolecules increases. This process is accompanied by an increase

in the number of elementary flow acts and intermolecular bonds, which are redistributed under the action of shear stress. This is evidenced by the increase in the heat of activation of the viscous flow.

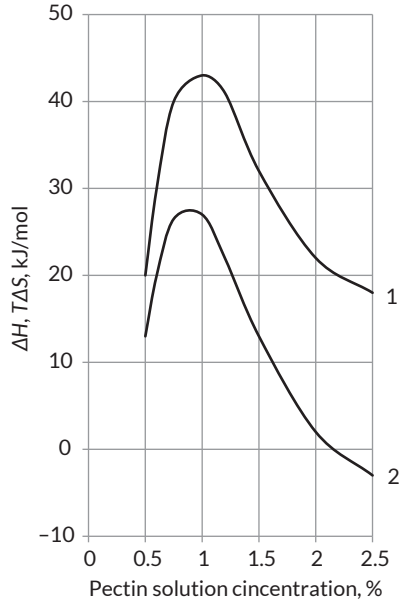

Fig. 13.4 Dependence of the activation parameters of the viscous flow of solutions on the concentration of sea buckthorn pectin:
1 – heat of activation (ΔH); 2 – entropy of activation ($T\Delta S$)

When the sea buckthorn pectin concentration is equal to the "critical" one, the total number of macromolecules becomes sufficient for the formation of a continuous three-dimensional mesh, and an ordered structure appears in the viscous solution. A further increase in the concentration of polysaccharide comes down to the involvement of new macromolecules in the resulting structure. The increase in the order of the system with an increase in the concentration of sea buckthorn pectin in the interval above the critical concentration is characterized by a significant decrease in the entropy of the activation of the viscous flow.

Taking into account the results of studies of polysaccharides, it can be assumed that when the structured system of pectins is sheared, the process of viscous flow is no longer due to the jumping of segments and individual macromolecules, but mainly

by the movement of larger supramolecular formations – aggregates and "domains". It is natural that the number of such kinetic units as aggregates or "domains" is significantly less than the total number of macromolecules, therefore, as the degree of aggregation increases, the number of contacts between kinetic units should decrease. In addition, the energy of interaction between individual aggregates is not so great, compared to the interaction of macromolecules within supramolecular structures. This is reflected in a decrease in the heat of activation of the viscous flow.

In the investigated concentration range of sea buckthorn pectin, the heat of activation and entropy change smoothly. As the polysaccharide concentration increases, the heat and entropy of activation first increase and then decrease, while the viscosity increases throughout the interval. It follows that at a concentration of sea buckthorn pectin less than the critical one, the effective shear viscosity depends mainly on the value of the heat of activation, while at a concentration greater than the critical one, the viscosity is determined mainly by the contribution of the entropy component.

Compared to the majority of industrial types of pectins that are currently used in the food and pharmaceutical industry, sea buckthorn pectin, which was studied, is characterized by a minimal value of the 'critical' concentration, which indicates its high thickening ability.

13.4.2 Research on the rheological properties of food systems containing sea buckthorn pectin

The study of rheological properties of food systems is a place for controlling the parameters of technological processes during the formation of optimal properties of the final product.

The tasks that study the influence of the components of the food system (in our case, new types of meat-vegetable canned food) on its rheological parameters are extremely important.

The inclusion of various components in the minced meat composition can cancel the quality indicators, in particular the structural and mechanical properties.

The object of the next study in this work was minced meat and vegetables with the addition of sea buckthorn pectin. The main components of the mass are water/food system (90/10).

Chicken fillet was ground in a meat grinder to a particle size of 1–2 mm. Bean flour and pectin were added to the minced chicken according to the recipes given in **Table 13.1**.

Table 13.1 Recipe for combined meat and vegetable minced meat

Component	Amount of component, g/100 g of raw material			
	F1	F2	F3	F4
Chicken trimmings	100	90	99	89
Bean flour	–	10	–	10
Sea buckthorn pectin	–	–	1	1

The components were thoroughly mixed, the minced meat samples were packed in polyethylene bags and stored at 4°C until testing.

The rheological parameters of the minced meat and vegetables were studied at 20°C.

In the food industry, the study of the dynamics of the ultimate shear stress is important for determining the consistency of products during storage or technological processing. Therefore, the dynamics of the ultimate shear stress of combined minced meat and vegetables with sea buckthorn pectin were studied depending on the shear rate.

The results of the studies are shown in **Fig. 13.5**.

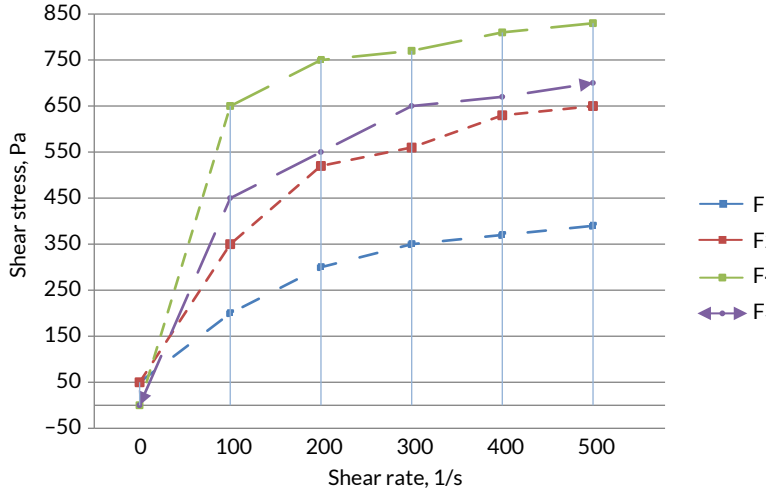

Fig. 13.5 Dynamics of ultimate shear stress of samples of combined meat and vegetable minced meat depending on the shear rate: F1 – chicken trimming; F2 – chicken trimming + bean flour; F3 – chicken trimming + sea buckthorn pectin; F4 – chicken trimming + bean flour + sea buckthorn pectin

In viscoelastic materials, the ultimate shear stress can depend on the rate of application of the load. With rapid loading, the material can behave as an elastic body with a higher ultimate stress, and with slow loading, as a viscous fluid with a lower ultimate stress. Changes in temperature can affect the strength of the material and its shear resistance. Typically, the ultimate shear stress decreases with increasing temperature. A material that has already undergone plastic deformation may have a different ultimate shear stress compared to an undeformed material. This phenomenon is called hardening. Chemical composition and microstructure are important factors. The presence of impurities, lattice defects, grain size, and other microstructural features can significantly affect the shear resistance of a material. Pressure, humidity, and other environmental factors can also affect the ultimate shear stress.

Analysis of the obtained rheograms (graphs of rheological parameters) allows to assess the mechanical stability of the paste and predict its behavior during production, storage and consumption. The mechanical stability of the paste means its ability to maintain a uniform consistency and physical structure for a certain time and under the influence of various mechanical factors. A mechanically stable paste should be uniform, plastic, spread well and not lose its properties under the influence of external factors. The work determined how the addition of sea buckthorn pectin affects the mechanical stability of experimental samples of the model base of the paste. For model samples F1 – chicken trimming; F2 – chicken trimming + bean flour; F3 – chicken trimming + sea buckthorn pectin; F4 – chicken trimming + bean flour + sea buckthorn pectin, the following results were obtained: for sample F1 – *MS* value = 1.22; for F2 – *MS* value = 1.29; for F3 – *MS* value = 1.12; for F4 – *MS* value = 1.14. A *MS* value greater than 1 indicates that the structure of the pate after destruction becomes weaker than it was before destruction. The higher the *MS* value, the greater the loss of structural strength after its disruption. For samples containing sea buckthorn pectin, a relatively small decrease in strength was found (*MS* ≈ 1.12–1.14). The *MS* value = 1.29 (sample containing chicken trimmings and bean flour) indicates a more significant loss of structural strength after destruction. Sample F2 lost approximately 30% of its initial strength, which may cause brittleness or a lower ability to restore its structure after damage. According to the results of the study, it can be concluded that the addition of sea buckthorn pectin leads to the fact that the product structure becomes less prone to significant loss of strength after mechanical impact, which leads to its destruction, i.e. such an additive improves the stability of the structure.

The dynamics of the ultimate shear stress shows how the value of the shear stress at which plastic deformation or fracture of the material begins varies depending on various factors.

In the context of food systems, the values of total, plastic and elastic strains reflect the response of a food product to an applied force or stress. Total deformation of a food system is the total change in the shape or volume of the product under the action of an external force. It includes both reversible (elastic) and irreversible (plastic) components. Total deformation is the total result of all changes that occur in the structure of the product under load. Plastic deformation of a food system is the irreversible part of the total deformation. This means that after the load is removed, the food product does not return to its original shape, but retains residual deformation. The magnitude of plastic deformation indicates the degree of irreversible changes in the structure of the product. For example, when spreading butter or pate on bread, the butter or pate undergoes plastic deformation, retaining its new shape after the force is removed.

Elastic deformation of a food system means that when an external force or stress is applied to a food product, it temporarily changes its shape or volume, but after the force is removed, it completely returns to its original state.

In the process of elastic deformation, changes occur in the interatomic or intermolecular distances in the structure of the food product. These changes are reversible, and when the load is removed, the molecules return to their original positions, restoring the original shape of the product.

The key characteristics of elastic deformation of food systems are: reversibility, temporality and dependence on the applied force. The first shows how after the load is removed the product completely restores its original shape and dimensions. Temporality shows that the deformation exists only as long as the external force acts. The dependence on the applied force characterizes the magnitude of the elastic deformation in relation to the applied force (within the limits of the elasticity of the material), which is described by Hooke's law (for solids) or similar dependencies for liquids and gels.

Elastic deformation can be clearly seen when analyzing various food systems, for example, during compression of sponge bread: when lightly compressed, the bread deforms slightly, but after the pressure is removed it returns to its original shape. An example such as the elasticity of jelly shows that slight oscillations or pressing on the jelly causes it to deform, but it quickly returns to its original shape. The elasticity of some fruits is also a visual demonstration of food systems, in which gently pressing a ripe but resilient peach can cause a small deformation that disappears when the pressure is removed. Elastic deformation is also characteristic of the change in volume of a liquid under pressure, since to some extent liquids can also undergo a small elastic deformation (change in volume) under pressure that disappears when it is removed.

Understanding elastic deformation is important for characterizing the textural properties of foods, their behavior during processing and storage, and for developing products with desirable sensory qualities. For example, elasticity is an important attribute for foods such as bread, paste, jellies, and some confectionery.

Understanding the relationship between elastic and plastic deformation is important for evaluating the texture, consistency, and behavior of foods during their production, storage, and consumption.

Products with high plastic deformation may be soft and easily deformable (e.g., paste).

The study of these deformations helps technologists develop products with desired properties and control their quality at different stages of production.

Fig. 13.6 shows the deformation parameters of experimental samples of the model base of combined meat-vegetable-pectin minced meat determined in the work.

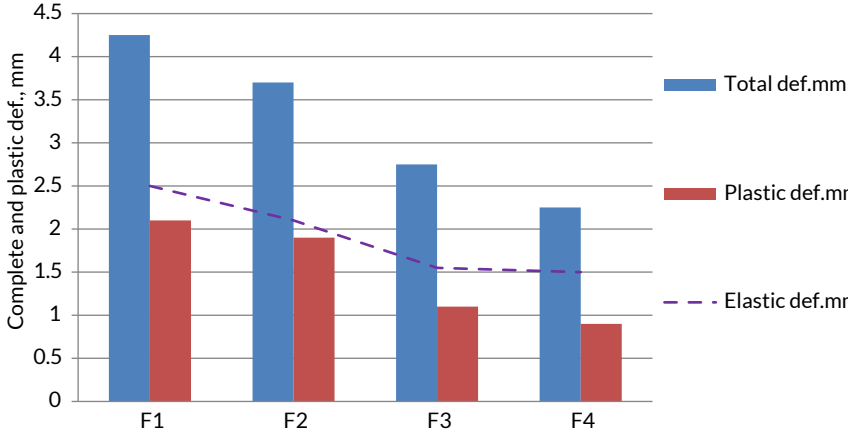

Fig. 13.6 Deformation parameters of experimental model samples of combined meat-vegetable-pectin minced meat: F1 – chicken trimming; F2 – chicken trimming + bean flour; F3 – chicken trimming + sea buckthorn pectin; F4 – chicken trimming + bean flour + sea buckthorn pectin

The highest values of total, plastic and elastic deformations were found in samples with the lowest shear stress – F1 and F2 (**Fig. 13.6**).

Small total, plastic and elastic deformations were found in samples F3 and F4, which contain sea buckthorn pectin. Small deformation of the pâté means that under the influence of external force (for example, when spreading, cutting or squeezing) it slightly changes its shape and at the same time retains its integrity, without

spreading or collapsing. After removing the external influence, the pâté can partially or completely return to its original shape.

In contrast, large total deformation may indicate too soft or liquid consistency, possible delamination.

From the point of view of the quality and properties of the pâté, small total deformation is a sign of high-quality pâté with a dense, but at the same time delicate structure.

Thus, the addition of sea buckthorn pectin led to a decrease in the total deformation of the model sample, which is a positive characteristic for the pate and indicates its high-quality consistency and stable structure.

13.4.3 Rheological study of composite pharmaceutical formulations based on sea buckthorn pectin

In the pharmaceutical sector, pectins represent a beneficial application for the creation of hydrogels. Hydrogel films have significant potential in pharmacy, as they provide a long-term and controlled release of drugs. This allows to reduce the frequency of drug administration, increase the effectiveness of therapy and reduce side effects. In addition to pharmaceutical applications, hydrogels are actively used in regenerative medicine to stimulate tissue regeneration. Thus, polymer hydrogels are a promising material for innovative technologies in biomedicine, in particular in drug delivery systems. Their unique properties provide a wide range of opportunities for the development of effective and safe therapy methods.

The physicochemical properties of hydrogels, in particular the degree of swelling, permeability and mechanical strength, determine their functionality. Pectins demonstrate high stability and can be modified by adding other polymers to achieve the desired characteristics. Polymer hydrogels based on pectin are three-dimensional polymer networks capable of absorbing and retaining a significant amount of water. One of the key characteristics of hydrogels is their ability to swell in an aqueous environment without losing structural integrity. This is achieved by chemical or physical crosslinking of polymer chains. The type of crosslinking determines the mechanical properties, stability and suitability of the hydrogel for a particular application. Despite the attractive properties of pectins, due to their hydrophilic nature and low water resistance, their use in sustained-release dosage forms is limited. One approach to further improve the characteristics of biopolymer films, in particular those based on pectin, is to combine them with other polymer matrices. Pectins can be modified by adding other polymers to achieve the desired characteristics. For a hydrogel with sea buckthorn pectin, it is most appropriate to use sodium alginate if one is aiming for

a completely natural, biodegradable hydrogel with good encapsulation capabilities and easy gelation (with the help of calcium). Sodium alginate is an ideal choice for food, pharmaceutical and biomedical applications where softness and compatibility with biological systems are important. Therefore, this study investigated the possibility of modifying sea buckthorn pectin by adding sodium alginate.

The study of the rheological properties of hydrogels is extremely important for many reasons, as they determine how the material will behave under the action of various forces and loads, as well as how it will interact with the environment and biological systems. These properties directly affect the production process, functionality and application of hydrogels.

Rheological studies of polymer compositions were carried out at different concentrations of pectin in the studied compositions. Based on the obtained results, flow curves were constructed (**Fig. 13.7**) illustrating the viscosity of sea buckthorn pectin-based solutions as a function of shear rate.

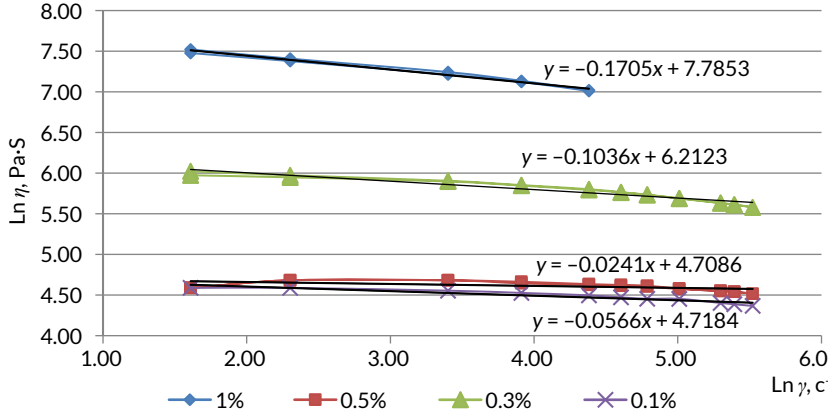

Fig. 13.7 Viscosity dependence of sea buckthorn pectin-based compositions on shear rate gradient

For all the curves presented, a decrease in viscosity (Ln η) is observed with increasing shear rate (Ln γ). This indicates pseudoplastic behavior (or shear thinning). This is a very common behavior for polymer solutions and hydrogels, which is explained by the orientation and deformation of polymer chains under shear loads, which reduces their resistance to flow. All slopes of the regression lines (the coefficient at x in the equation $y = mx + b$) are negative, which confirms the decreasing dependence of viscosity on shear rate. All points for each sample are approximated

by straight lines, which indicates that the dependence of Ln η on Ln γ is linear. This is typical for flow models, such as the Ostwald-de Waele power law, which in logarithmic coordinates has the form

$$\text{Ln}\,\eta = (n - 1)\,\text{Ln}\,\gamma + \text{Ln}\,K,$$

where n – the flow behavior index; K – the consistency coefficient.

For example, for the upper curve ($y = -0.1705x + 7.7853$), let's obtain: $n - 1 = -0.1705 \Rightarrow n = 1 - 0.1705 = 0.8295$, indicating pseudoplastic behavior ($n < 1$), and $\text{Ln}\,K = 7.7853 \Rightarrow K = e^{7.7853} \approx 2404.9$.

The difference in slopes and initial viscosity values between the curves indicates that the concentration significantly affects the rheological properties of the hydrogels, with the sample with a pectin content of 1.0% being the most viscous and the most pronounced pseudoplastic. It is known that classical pseudoplastics, unlike Bingham plastics, do not have a yield point. This means that they begin to flow even under very low shear stresses, albeit with very high viscosity. The graph does not show an initial viscosity "shelf", which may indicate the absence of a yield point. The high initial viscosity at rest provides shape stability (e.g. for encapsulation). At the same time, the shear thinning ability makes the material easily pumpable, extruded or injected under pressure. This is very important for applications such as injectable hydrogels for drug delivery. After the shear stress is removed (e.g. after extrusion from a nozzle), the viscosity of the material increases rapidly, allowing it to hold its shape and preventing it from flowing. The pseudoplastic behavior provides a pleasant tactile sensation when applied (easy spreading) and the stability of the product in the package.

So, in this case, the composition of sea buckthorn pectin polymers (concentration 1%) and sodium alginate is a material that is very well structured at rest, but easily deforms and flows under mechanical stress, after which it can restore its original structure, which makes it very valuable for many practical applications.

13.5 Conclusion

This work shows that sea buckthorn pectin is a promising ingredient with a wide range of applications in the food and pharmaceutical industries. Its unique structural-forming and functional properties open up new opportunities for creating innovative products with improved quality characteristics and benefits for consumers.

The dependence of the solution viscosity on the concentration of sea buckthorn pectin has been established and it has been proven that the studied pectin from sea buckthorn peel is characterized by a minimum value of the "critical" concentration – 1%, which indicates its high thickening ability.

The heat and entropy of activation of the viscous flow of a sea buckthorn pectin solution have been determined in order to obtain a thermodynamic idea of the structural aspects of the processes occurring in solutions of this polysaccharide. In the studied range of sea buckthorn pectin concentrations, the heat of activation and entropy change symbiotically.

A correlation between the formation of the structure and the rheological properties of pectin solutions has been revealed. The results of rheological and physicomechanical studies showed that sea buckthorn pectin added to the raw materials significantly affects the structure of combined minced meats – chicken trimming + bean flour + sea buckthorn pectin. It was found that both total deformation and its components – plastic and elastic – decreased upon addition of sea buckthorn pectin to the food system (from 4.15 mm to 2.25 mm). The experimental data obtained indicate that the addition of sea buckthorn pectin improved the stability and deformation parameters of experimental model samples of combined minced meats, which contributes to the formation of a stable combined food system with a strong structure.

The rheological analysis of pharmaceutical composite formulations based on sea buckthorn pectin modified with sodium alginate demonstrated that the 1.0% pectin sample behaved as a classical viscous pseudoplastic fluid, which is highly relevant for various applied uses.

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CHAPTER 14

Innovative technology for high-quality functional alcoholic beverages based on tea-aromatic raw materials with antioxidant activity

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Abstract

The feasibility of using water-alcohol infusions of tea-herbal raw materials (*Ilex paraguariensis*, *Camellia sinensis*, *Citrus spp.*) for the production of alcoholic beverages has been substantiated. These components are characterized by high bioactivity, the stability of polyphenolic compounds in alcoholic media, appealing aroma, and favorable sensory properties, making them an effective basis for innovative functional beverages.

The antioxidant activity of the obtained infusions was determined. The highest reducing capacity (RE_{plant}) was observed in citrus peel infusions (up to 204.00 mV for orange peel), green tea (56.06 mV), and yerba mate (59.02 mV). This indicates the presence of a significant amount of bioactive compounds that retain antioxidant potential even in ethanol-containing systems.

The potential for modifying infusions based on tea-aromatic compositions within alcoholic beverage technology has been explored. It was established that the optimal mass ratio of components ω = 20/75/5% (mate/tea/citrus peel) provides a balanced flavor, reduces the bitterness of mate, enhances the aroma with fresh fruity notes, and increases the overall sensory evaluation score (up to 9.82 points – for mate/green tea/orange peel).

Sensory evaluation of the infusions confirmed their suitability for commercial development. All infusions received high sensory scores ranging from 9.63 to 9.82

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on a 10-point scale, indicating strong consumer appeal and potential for implementation in the restaurant industry for the creation of new-generation functional alcoholic beverages.

Optimized formulations for functional alcoholic beverages enriched with antioxidant tea-herbal infusions have been developed. The formulation includes:

– 38.49% of the infusion (mate/tea/citrus peel in a 20/75/5% ratio);
– 7.54% brandy;
– 53.08% sugar syrup;
– vanillin;
– citric acid;
– caramel coloring;
– ethanol/water to adjust the alcohol content to 20% vol.

This ensures a functional and sensory balance while maintaining market viability.

The integration of antioxidant-rich infusions based on *Ilex paraguariensis*, *Camellia sinensis*, and *Citrus spp.* into alcoholic beverage technology offers new opportunities for the restaurant industry to expand product offerings, enhance functional value, and cater to the growing demand for health-oriented and innovative beverages.

Keywords

Redox potential, blending, functional alcoholic beverage, water-alcohol infusions, antioxidant, tea-aromatic raw materials, *Ilex paraguariensis*, *Camellia sinensis*, *Citrus spp.*

14.1 Introduction

In recent years, there has been growing interest in the development of functional alcoholic beverages that combine sensory appeal with health-enhancing properties. Among such innovations, tea- and plant-based infusions enriched with bioactive compounds are gaining attention due to their potential antioxidant, adaptogenic, and tonic effects. Yerba mate (*Ilex paraguariensis*), various types of tea (*Camellia sinensis*), and citrus peels (*Citrus spp.*) have been widely recognized for their high content of polyphenols, flavonoids, and essential oils, which contribute both to health benefits and to the complexity of flavor and aroma.

Water-alcohol infusions made from these plant materials offer a promising basis for the creation of innovative liqueurs and spirits. However, the success of such products depends not only on their functional properties but also on their sensory characteristics, which are critical for consumer acceptance. Balancing the bitter, astringent, and aromatic components of ingredients like mate and tea requires careful formulation and optimization.

14.2 Tea-aromatic compositions

14.2.1 Varieties and geographical distribution of *Ilex paraguariensis*

Ilex paraguariensis, a plant of significant ethnobotanical and economic value, exists in two recognized morphological varieties: *Ilex paraguariensis Saint Hilaire var. paraguariensis*, which is widely used in industrial processing, and *Ilex paraguariensis var. vestita (Reisseck) Loes*, which, despite its taxonomic classification, has not found application in commercial use [1].

This evergreen species is indigenous to the subtropical regions of South America, predominantly found in Argentina, Uruguay, Paraguay, and Brazil [1, 2]. Its natural habitat spans the Upper Paraná Atlantic Forest biome, where it thrives under specific ecological conditions conducive to the development of its bioactive compounds.

The leaves and stems of *Ilex paraguariensis St. Hil.* are a rich natural source of caffeine and serve as a traditional stimulant beverage, often replacing or complementing tea (*Camellia sinensis*) and coffee (*Coffea spp.*) in the dietary practices of millions [1]. Various infusion methods of this plant have developed across the region, reflecting both cultural and functional preferences [1]:

– *chimarrão* (Brazil) or *mate* (Spanish-speaking countries) – a hot water infusion prepared from dried green leaves and young branches;

– *tererê* (Brazil) or *tereré* (Paraguay) – a cold infusion of the same plant material, particularly popular in warm climates;

– *chá-mate* or *mate tea* – an infusion of roasted leaves, commonly consumed hot in Brazil;

– *instant mate tea* – a soluble variant derived from processed roasted leaves for convenience consumption.

These forms underscore the versatility of Ilex paraguariensis as both a traditional and industrial ingredient in the production of functional beverages, contributing to its growing significance in global nutraceutical markets.

14.2.2 Bioactive constituents of Ilex paraguariensis

Ilex paraguariensis St. Hil. are an important source of biologically active compounds (**Fig. 14.1**) [2, 3]:

– phenolics [3–6] → simple phenols → phenolic acids [7] → hydroxycinnamic acids: caffeic acid [6, 8]; ρ-coumaric acid [8]; ferulic acid;

– phenolics [2, 9–11] → simple phenols → phenolic acids [12] → hydroxybenzoic acids: gallic acid [6, 8]; syringic acid;

– phenolics → polyphenols [11, 13] → flavonoids [1, 3] → flavonols [4] (rutin, quercetin, kaempferol) [3];

– phenolics → polyphenols → flavonoids → flavonols: catechins;

– phenolics → polyphenols → non-flavonoids → tannins [1, 2], which have an effect on health: inhibition of lipid-peroxidation, mutagenicity of carcinogens and tumor promotion, as well as host-mediated antitumor activity and antiviral activity;

– chlorogenic acids [1–5, 8] – a related polyphenol family of esters, including hydroxycinnamic acids (caffeic, ferulic, *p*-coumaric) with quinic acid. Chlorogenic acid derivatives [5, 6, 8, 11]:

a) caffeoylquinic acids (3-O-caffeoylquinic acid, 4-O-caffeoylquinic acid, 5-O-caffeoylquinic acid);

b) dicaffeoylquinic acids (3,4-dicafeoylquinic acid; 3.5-dicafeoylquinic acid; 4.5-dicafeoylquinic acid);

c) feruloyquinic acid;

d) *p*-coumaroylquinic acids.

Chlorogenic acids is a multiple health functions [14]: such as antiviral, anti-inflammation, hypoglycemic, hepatoprotective activities, antioxidation;

– purine alkaloids – methylxanthines [1–3, 5, 8]: caffeine; theobromine; theophylline;

– saponins [1–4], which affect the flavor of *mate* extract, provide hypocholesterolemic properties [2] – bind bile salts [15]; sapogenins [15];

– chlorophyll [2, 16] have properties to benefit the human body, such as antioxidant activity, antimutagenic activity, modulation of xenobiotic metabolizing enzymes, and induction of apoptotic events in cancer cell lines [16];

– organic acids, amino acids [3], fatty acids;

– mineral substances [3];

– vitamins [1, 3, 4]: A, B, C, E [1];

– free sugars, polysaccharides [17];

– volatile compounds (linalool, 3-allylguaiacol, O ± -ionone, OI-ionone, O ± -terpineol, octanoic acid, geraniol, 1-octanol, nerolidol, geranylacetone, eugenol, 2.6-dimethyl-1.7-octadien-3-ol, methyl salicylate) [18].

Mate infusion has a characteristic bitter taste that resembles strong green tea, a specific aroma [19] and a light green color.

Along with the traditional use of *mate* drinks, *Ilex paraguariensis* is used as an energy tea with other herbs, a weight loss agent, in the production of beer, creams, candy, and other non-traditional uses [1].

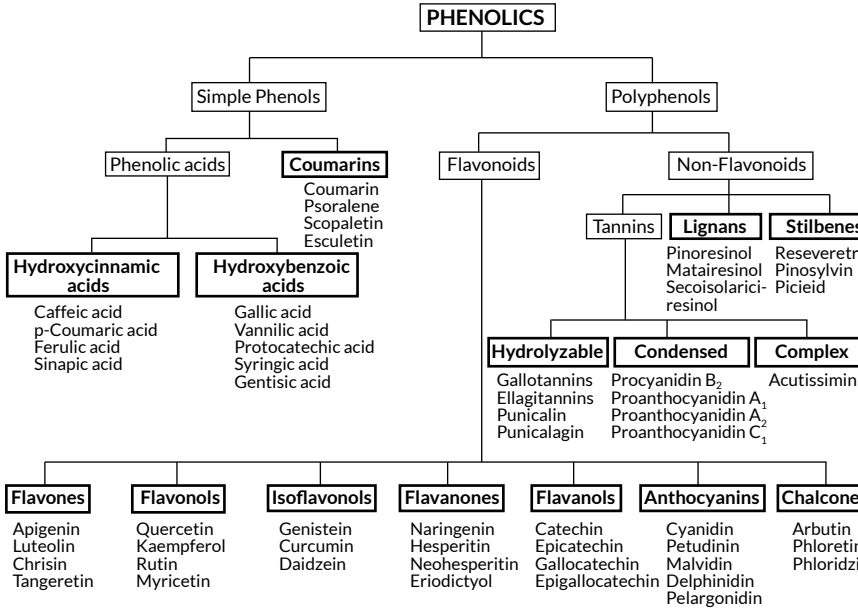


Fig. 14.1 Classification of phenolic compounds
Source: [9]

14.2.3 Properties of *Ilex paraguariensis*

Ilex paraguariensis St. Hil has many benefits for human health [3, 6, 19, 20], is used as a therapeutic agent [1], due to its supposed pharmacological, medicinal properties [1]:

– stimulating properties [1, 2, 15], due to the caffeine content in *mate* [2];
– anti-anxiety properties [20];
– immunomodulatory profile;
– vaso-dilating properties [1];
– cardioprotective properties [11];
– anti-inflammatory [3]; antibacterial; antimicrobial properties [6];
– antigenotoxic properties [21], showing antimutagenic effects [1] and subsequent DNA repair [20, 21];
– anti-cancer [3] and antitumor properties due to saponins in *mate* [22];
– anti-rheumatic properties [23];
– neuroprotective effects [20, 24];

– gastroprotection [17];
– detoxifying properties [15];
– diuretic properties [3];
– hypolipidemic – lipid-lowering properties [1]; hypocholesterolemic properties [3] – lowering cholesterol, thanks to saponins in *mate*, with an antiatherosclerotic effect;
– hepatoprotective [3];
– anti-glycation effects [1, 13], due to chlorogenic and caffeic acid in *mate*;
– antidiabetic properties [13];
– anti-obesity properties [3], for weight loss [1], due to the ability of caffeine in *mate* to increase thermogenesis;
– antioxidant properties [1–3, 7, 8, 10, 13, 21, 25, 26].

14.2.4 Antioxidant properties of *Ilex paraguariensis*

In biological systems, antioxidant defense systems are made up of agents that prevent the harmful effects of free radicals. Antioxidants are the agents, which scavenge free radicals [14] otherwise reactive oxygen species and prevent the damage caused by them, interfering with the oxidative/antioxidative potential of cells, by improving antioxidant status [27]. Free radicals have been associated with pathogenesis of various disorders like cancer, diabetes, cardiovascular diseases, autoimmune diseases, neurodegenerative disorders and are implicated in aging, chronic diseases [27]; cell and tissue damage induced by oxidative stress is related to the etiology of chronic diseases [8].

Antioxidants are beneficial and could display a useful role in human homeostasis, however, they could be pro-oxidants as well [12]. Homeostasis – relativity of dynamic constancy of composition and properties of internal environment and stability of basic physiological functions of an organism. Redox reactions affect the ratio of energy to support homeostasis.

Antioxidant activity of *Ilex paraguariensis St. Hil.* is related to the presence of several compounds:

– phenolics [27] → simple phenols → phenolic acids [12] → hydroxycinnamic acids: caffeic acid;
– phenolics → simple phenols → phenolic acids [12] → hydroxybenzoic acids: gallic acid [10];
– phenolics [10] → polyphenols → flavonoids [10] → flavonols: catechins [10], epicatechin [10];
– phenolics → polyphenols → flavonoids → flavonols: rutin;

– phenolics → polyphenols → non-flavonoids → tannins → condensed: procyanidin B2 [10];

– chlorogenic acids [14]: particularly caffeoyl derivatives;

– quercetrin [10];

– purine alkaloids – methylxanthines: caffeine [10]. On the contrary, caffeine induced lipid peroxidation of linoleic acid acting as a pro-oxidant compound.

Endogenous antioxidant mechanisms include antioxidant enzymes activities, such as glutathione peroxidase (GPx), superoxide dismutase (SOD), and catalase (CAT), and the reduced form of glutathione, among others [8]. However, endogenous antioxidant defenses are not always sufficient to completely counteract oxygen reactive species [8].

14.2.5 Characteristics of *Camellia sinensis*

Tea (*Camellia sinensis*) has gained much attention due to its health-promoting benefits, including antimutagenic, anticancer and antiapoptotic [28, 29], neuroprotective [30], hypoglycemic and antihyperglycemic, antioxidant [28, 29], antimicrobial, and inflammatory effects [31]. These biological activities [10] are associated in part to the antioxidant activity of chemical compounds present in teas, especially flavonoids and phenolic acids [10]. Classification of tea by oxidation (fermentation) level: fermented (black tea); partially fermented (red, yellow tea); unfermented (green, white tea).

14.2.6 Comparative characteristics of *Ilex paraguariensis* and *Camellia sinensis*

The content of the total phenolic compounds of the teas ranged from 672.87 mg GAE/L (*Ilex paraguariensis*) to 1034.48 mg GAE/L (*Camellia sinensis*) and the flavonoid content ranged from 176.04 mg CTE/L (*Ilex paraguariensis*) to 179.88 mg CTE/L (*Camellia sinensis*) (**Table 14.1**) [10]. This is confirmed by the data [13], the level of polyphenol in the extract of *Ilex paraguariensis* is higher than in green tea, this confirms the ability to inhibit the formation of glycation end products of *Ilex paraguariensis* compared to green tea [13] and prevents lipid peroxidation [21]. Green tea and *mate* tea present anti-carcinogenic activity [21].

The results showed that the inhibition of DPPH ranged from 49.66% (*Ilex paraguariensis*) to 68.60% (*Camellia sinensis*) of reduction, and the FRAP results varied from 5065.75 μmol TE/L (*Ilex paraguariensis*) to 10331.19 μmol TE/L (*Camellia sinensis*).

Table 14.1 Total phenolics, flavonoids, antioxidant capacity and chemical composition of teas

Name of indicators	Herbal species	
	Camellia sinensis	Ilex paraguariensis
Phenolic compounds		
– total phenolics (mg GAE/l)	1034.48 ± 416.24	672.87 ± 126.25
– flavonoids (mg CTE/l)	179.88 ± 32.41	176.04 ± 40.50
Antioxidant activity		
– DPPH (% reduction)	68.60 ± 22.40	49.66 ± 9.59
– FRAP (μM TE/l)	10331.19 ± 4802.91	5065.75 ± 298.61
Chemical composition (mg/l)		
– gallic acid	198.73 ± 78.02	n.d.
– epicatechin	68.55 ± 105.39	n.d.
– procyanidin b2	3.67 ± 8.77	n.d.
– quercitrin	21.13 ± 15.76	n.d.
– chlorogenic acid	5.22 ± 6.33	199.42 ± 149.38
– catechin	31.76 ± 58.49	6.67 ± 13.33
– caffeine	5485.23 ± 1637.22	1244.63 ± 711.13
– coumaric acid	n.d.	n.d.
– procyanidin b1	n.d.	n.d.
– quercetin	n.d.	n.d.

Note: results expressed as mean ± SD (n = 3); n.d. = not detected or values below LOD
Source: [10]

The contents of individual phenolic compounds varied within tea. Gallic acid (198.73 mg/L), epicatechin (68.55 mg/L), procyanidin B2 (3.67 mg/L) and quercitrin (21.13 mg/L) were found only in *Camellia sinensis* teas, and the contents of chlorogenic acid ranged from 5.22 mg/L (*Camellia sinensis*) to 199.42 mg/L (*Ilex paraguariensis*), catechin from 6.67 mg/L (*Ilex paraguariensis*) to 31.76 mg/L (*Camellia sinensis*), and caffeine from 1244.63 mg/L (*Ilex paraguariensis*) to 5485.23 mg/L (*Camellia sinensis*) [10].

Coumaric acid, procyanidin B1 and quercetin were not detected in *Camellia sinensis* and *Ilex paraguariensis* tea samples [10].

Thus, it is important to monitor the phenolic composition and the biological activity of teas consumed by a large part of the population in order to correlate their benefits with human health [10].

14.2.7 The ethanol extract of *Ilex paraguariensis*

The ethanol extract *Ilex paraguariensis St. Hil.* presents antimicrobial activity against food pathogens was effective in inhibiting *S. aureus*, *L. monocytogenes* and *S. Enteritidis*, to be related to the presence of compounds derived from chlorogenic acid [6]. The ethanol extract was active at pH 7 and at pH 8 [6]. *Ilex paraguariensis St. Hil.* is thus a potential source for the extraction of antimicrobial compounds for use by the food industry as a natural preservative in foods and beverages [6]. For antioxidant action of *Ilex paraguariensis St. Hil.* use of ethanol as extractor liquid should be considered for the extract procedure in order to obtain greater amounts of antioxidant compounds may be obtained.

14.2.8 Antioxidant properties and chemical composition of citrus peels (*Citrus spp.*)

Recent studies on *Citrus spp.* peel extracts have demonstrated significant antioxidant activity, with detailed characterization of bioactive compounds across three different varieties [32]. The findings highlight variations in phenolic content and radical scavenging potential, reinforcing the potential use of these peels as natural antioxidants in food and pharmaceutical applications.

14.2.9 Relevance of the research direction

Water-alcohol infusions are produced by extracting dried plant materials using a water-alcohol mixture – a technique widely employed in alcoholic beverage production within the restaurant industry. This process not only enhances the sensory characteristics of the beverage but also enriches it with bioactive compounds, significantly increasing its antioxidant capacity.

The relevance of this research lies in the development of innovative water-alcohol infusions based on tea-aromatic compositions containing *Ilex paraguariensis* (yerba mate), *Camellia sinensis* (tea), and citrus species (*Citrus* spp.), known for their rich phytochemical profiles and functional properties. These compositions demonstrate pronounced antioxidant activity, contributing to the protection of the human body from oxidative stress-induced damage, while also improving the nutritional value and overall quality of alcoholic beverages.

The aim of this research is to determine the antioxidant capacity of water-alcohol infusions prepared from tea-aromatic compositions based on *Ilex paraguariensis*,

Camellia sinensis, and *Citrus* spp., and to evaluate their potential for developing innovative, high-quality functional alcoholic beverages within the restaurant industry.

To achieve this aim, the following objectives are set:

– to justify the feasibility of using water-alcohol infusions of tea-aromatic compositions containing *Ilex paraguariensis*, *Camellia sinensis*, and *Citrus* spp. in alcoholic beverage production;

– to determine the antioxidant capacity of the prepared infusions;

– to explore various modifications of infusions based on these plants within beverage technologies;

– to conduct sensory evaluation of the infusions and assess their suitability for commercial development of innovative beverages;

– to develop optimized formulations for functional alcoholic beverages enriched with antioxidant-rich tea-aromatic infusions.

The integration of antioxidant-rich infusions based on *Ilex paraguariensis*, *Camellia sinensis*, and citrus peels (*Citrus* spp.) into alcoholic beverage technology opens promising avenues for restaurants to diversify their product offerings, enhance the functional value of drinks, establish a differentiated market presence, and support the development of a favorable brand image.

14.3 Materials and methods

14.3.1 Materials

The study used samples of plant raw materials: *Ilex paraguariensis*; *Camellia sinensis* tea in three types – green, red, and black; as well as *Citrus spp.* (citrus peels) – lemon, orange, and mandarin. A 40% vol. water-alcohol mixture was used as the control sample.

14.3.2 Methods of obtaining water-alcohol infusions

Drying of plant raw materials was carried out until constant moisture content was achieved, ranging between 6–8%. Collected and inspected raw materials were spread out on clean white paper, each type separately. The plant materials were then cut with scissors into pieces approximately 3 × 3 mm in size. Samples weighing 4 g were placed into dark glass bottles and poured over with 100 ml of a 40% vol. water-alcohol mixture. The bottles were sealed and placed in a Durocell dry air thermostat at 40°C for 48 hours. The resulting infusions were cooled to room temperature, then filtered.

Subsequent analyses included measurement of active acidity (pH) using a pH meter equipped with a combined glass electrode. Redox potential (*RP*) was measured using a combined platinum redox electrode in potential measurement mode [26, 33–36].

14.3.3 Methods for determining active acidity and redox potential

The active acidity (*pH*) of the obtained water-alcohol herbal infusions was measured using a precision pH meter "pH-150 MA" equipped with a combined glass electrode "ESC 10601/4", providing high sensitivity and stability in aqueous-alcoholic environments. Redox potential (*RP*) was determined using the same instrument "pH-150M" in the potentiometric mode with a redox platinum electrode "ERP-105", ensuring reliable measurements of oxidation-reduction balance.

To assess the antioxidant properties of the herbal extracts, the *RP* method was applied according to protocols described by [26, 33–36]. This method is based on the evaluation of *RP* differences in water-alcohol media as an indicator of the redox state and antioxidant potential of the tested samples.

The advantages of this approach lie in its transparency, methodological simplicity, analytical specificity, reproducibility of results, and suitability for routine analysis. In addition, the method is applicable for assessing total antioxidant activity in complex multicomponent systems, including synergistic and multifunctional antioxidants commonly found in tea-aromatic compositions and citrus peel extracts. Its sensitivity to changes in oxidation-reduction balance enables the detection of even moderate antioxidant effects in experimental formulations, making it highly effective for research in functional beverage development.

14.3.4 Research of redox potential from hydrogen ion activity in water-alcohol infusions of vegetable raw materials

To evaluate the antioxidant potential of plant-based water-alcohol infusions, the relationship between the hydrogen ion activity (pH) and redox potential (*Eh*) of the medium is critically important. In a water-alcohol system, this relationship reflects the medium's tendency to accept or donate electrons, thus serving as a fundamental parameter for assessing antioxidant capacity.

According to experimental findings [34, 35], a shift of one *pH* unit in the water-alcohol mixture corresponds to an approximate change in redox potential of 42 mV, expressed by the following empirical equation

$$Eh_{min} = 502 - 42\,pH, mV. \quad (14.1)$$

Within the pH range of 2.0 to 11.0, which corresponds to typical values observed in hydroalcoholic infusions, the calculated redox potential of the base solvent system (Eh_{min}) ranges from 418 mV to 40 [34, 35]. This model provides a theoretical baseline for comparing the redox behavior of functional infusions.

The actual redox potential (Eh_{act}) of the obtained infusions was measured using a platinum redox electrode, and the difference between the theoretical and measured potentials was used to characterize the contribution of the plant material to the oxidative-reductive properties of the system. This difference, denoted as RE_{inf}, is calculated as [34, 35]

$$RE_{inf} = Eh_{min} - Eh_{act}, mV. \quad (14.2)$$

Furthermore, the net antioxidant capacity of the plant material (RE_{plant}), independent of the solvent background, was calculated as the difference between RE_{inf} and the redox effect of the control sample (RE_{sol}), according to [34, 35]

$$RE_{plant}=RE_{inf} - RE_{sol}, mV. \quad (14.3)$$

This enhanced methodology enables the differentiation of antioxidant activity contributed specifically by the plant raw materials (*Ilex paraguariensis*, *Camellia sinensis* of various fermentation levels, and *Citrus spp.* peels). It is particularly effective in identifying multifunctional antioxidants in complex matrices and provides a reproducible, sensitive, and technically accessible framework for the development of functional beverages in the alcohol industry [34, 35].

14.3.5 Expert method of sensory evaluation

The sensory evaluation of the developed water-alcohol infusions was carried out using an expert method, which involves the participation of qualified and experienced specialists with heightened sensitivity to organoleptic characteristics of alcoholic beverages. This method is widely recognized for its reliability and reproducibility in assessing quality indicators such as clarity and color, aroma, taste, and overall score on a 10-point scale (**Table 14.2**).

The experts independently assessed the samples using standardized evaluation protocols, taking into account both quantitative and qualitative sensory attributes.

Table 14.2 Overall score assessment of quality for liqueur and vodka drinks based on a 10-point scale

Parameter	Description (organoleptic characteristic)	Score range	Score
Clarity and Color	Clear liquid with gloss and bright color typical for product type; cloudy/emulsion products have uniform consistency and color	1.9–2.0	Excellent
	Clear liquid without gloss, color typical but insufficiently expressed; cloudy/emulsion products uniform but less vivid color	1.8–1.9	Good
	Clear liquid without gloss, insufficient color; cloudy/emulsion products non-uniform consistency and weak color expression	< 1.8	Unsatisfactory
Aroma	Bright, characteristic of product type	3.8–4.0	Excellent
	Characteristic but weakly expressed	3.6–3.8	Good
	Weak or uncharacteristic	< 3.6	Unsatisfactory
Taste	Harmonious, balanced, characteristic of product type	3.8–4.0	Excellent
	Characteristic and pleasant	3.6–3.8	Good
	Insufficiently expressed or uncharacteristic	< 3.6	Unsatisfactory
Overall Score	Sum of parameters	9.5–10.0	Excellent
		9.0–9.5	Good
		< 9.0	Unsatisfactory

This approach has proven effective in differentiating subtle variations in flavor and aroma profiles associated with the type of herbal raw material used (e.g., *Ilex paraguariensis*, *Camellia sinensis* of different fermentation levels, and *Citrus spp.* peels), as confirmed in prior research [26, 33–37].

14.4 Results and discussions

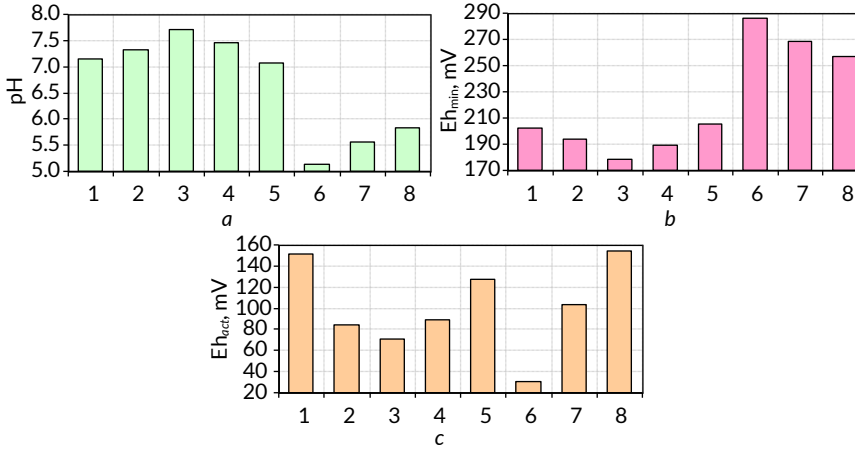
14.4.1 Results of the study of the antioxidant capacity of water-alcohol infusions of tea-aromatic raw materials

Water-alcohol infusions of tea-aromatic raw materials (*Ilex paraguariensis*, *Camellia sinensis*, *Citrus* spp.) exhibit diverse physicochemical and organoleptic properties (**Fig. 14.2, 14.3**). These differences arise from the botanical diversity of the raw materials and their degree of fermentation, which significantly influence the content

of phenolic compounds, essential oils, organic acids, and the dynamics of their extraction during infusion.

A water-alcohol mixture was used as a solvent: pH 7.14 units pH; Eh_{min} 202.12 mV; Eh_{act} 151.00 mV; RE_{sol} 51.12 mV; *S.e.* 9.61 points (color – colorless; aroma – alcoholic; taste – moderately burning, empty).

The *pH* range of the infusions (**Fig. 14.2, *a***) varied from 5.14 (orange peel) to 7.71 (green tea). Notably, citrus-based infusions (particularly orange, mandarin, and lemon peels) exhibited the lowest pH values (5.14–5.84), which can be attributed to the presence of significant amounts of organic acids (citric, malic, and ascorbic acids). This creates a mildly acidic medium favorable for the stability of certain flavonoids. In contrast, tea and mate infusions displayed a neutral or slightly alkaline environment (pH > 7), suggesting high buffering capacity due to the presence of tannins, alkaloids (e.g., caffeine, theobromine), and organic acid salts. These *pH* values are important for preserving antioxidant activity, as polyphenols demonstrate the highest stability in slightly alkaline conditions [38].



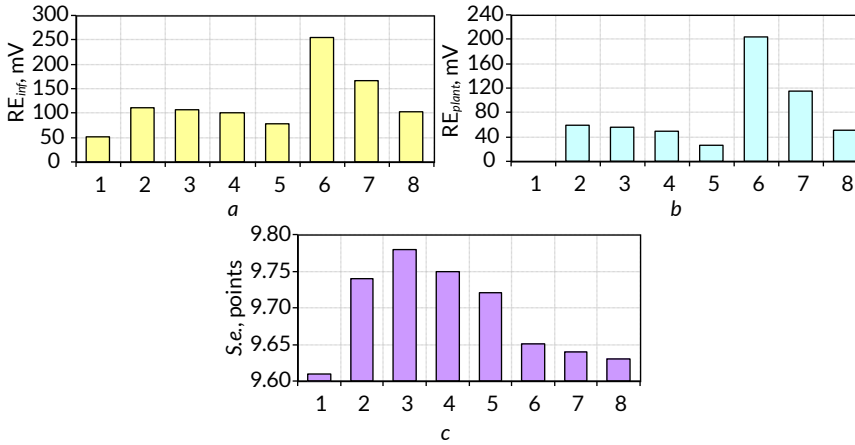
1 – water-alcohol mixture (control); 2 – water-alcohol infusion of mate;
3 – water-alcohol infusion of green tea; 4 – water-alcohol infusion of red tea;
5 – water-alcohol infusion of black tea; 6 – water-alcohol infusion of orange peel;
7 – water-alcohol infusion of mandarin peel; 8 – water-alcohol infusion of lemon peel

Fig. 14.2 Characteristics of water-alcohol infusions: *a* – active acidity (pH); *b* – the minimum theoretical value of *RP* (Eh_{min}); *c* – actual measured of *RP* (Eh_{act})

The minimum theoretical value of *RP* (Eh_{min}) for water-alcohol infusions was obtained, which has a value from 178.18 mV (green tea) to 286.12 mV (orange

peel) (**Fig. 14.2, *b***). Redox potential (*Eh*) parameters provided valuable insight, with the lowest recorded actual redox potential (Eh_{act}) being – 31.00 mV in the orange peel infusion, indicating exceptionally high reducing power (**Fig. 14.2, *c***). This corresponds with literature data on the ability of flavonoids to lower the redox potential of the medium [39].

The highest infusion redox potential (RE_{inf}) was observed in orange peel (255.12 mV), indicating excellent reducing activity that surpasses that of tea infusions (**Fig. 14.3, *a***). Mate exhibited a relatively high RE_{inf} of 110.14 mV, though lower than the values for citrus infusions. This may be explained by the presence of chlorogenic acid, which exhibits antioxidant activity in aqueous solutions but is less effective in water-alcohol infusions [14]. Black tea showed the lowest RE_{inf} of 78.06 mV, reflecting decreased antioxidant potential due to fermentation of polyphenolic compounds, as confirmed by several studies [40].



1 – water-alcohol mixture (control); 2 – water-alcohol infusion of mate;
3 – water-alcohol infusion of green tea; 4 – water-alcohol infusion of red tea;
5 – water-alcohol infusion of black tea; 6 – water-alcohol infusion of orange peel;
7 – water-alcohol infusion of mandarin peel; 8 – water-alcohol infusion of lemon peel

Fig. 14.3 Characteristics of water-alcohol infusions: *a* – recovery energy of infusions (RE_{inf}); *b* – the energy of reduction/oxidation of vegetable raw materials (RE_{plant}); *c* – sensory evaluation indicators (*S.e.*)

Interpretation of RE_{plant}, defined as the difference between RE_{inf} and the RE_{sol} of the control solution (water-alcohol mixture), allows evaluation of the additional reducing activity generated solely by the plant material (**Fig. 14.3, *b***). According to this

parameter, orange peel (RE_{plant} = 204.00 mV), mandarin peel (RE_{plant} = 114.36 mV), and lemon peel (RE_{plant} = 51.60 mV) convincingly demonstrate their potential for developing functional beverages with pronounced antioxidant effects. In contrast, tea infusions showed RE_{plant} values below 60 mV (the lowest being 26.94 mV for black tea), indicating moderate additional antioxidant activity.

The analysis of the reducing activity (RE_{plant}) of water-alcohol infusions of tea raw materials reveals variability in antioxidant potential depending on the type of plant material. The highest additional reducing activity was demonstrated by the infusion of mate (*Ilex paraguariensis*), with RE_{plant} value of 59.02 mV, indicating a significant ability to lower the redox potential of the medium. Comparable results were observed for green tea (*Camellia sinensis*) infusion – 56.06 mV – which may be attributed to its high content of catechins and other non-oxidized polyphenols. The infusion of red tea showed a slightly lower RE_{plant} value of 48.98 mV, reflecting a partial reduction in antioxidant activity due to fermentation processes. The lowest RE_{plant} value was recorded for black tea – 26.94 mV – which, according to literature data, results from the extensive fermentation of the polyphenolic fraction. This is supported by research [10], which suggests that antioxidant efficiency depends on the type of tea and the content and type of phenolic compounds present in each type. The level of polyphenol in the extract of Ilex paraguariensis is higher than in green tea [13].

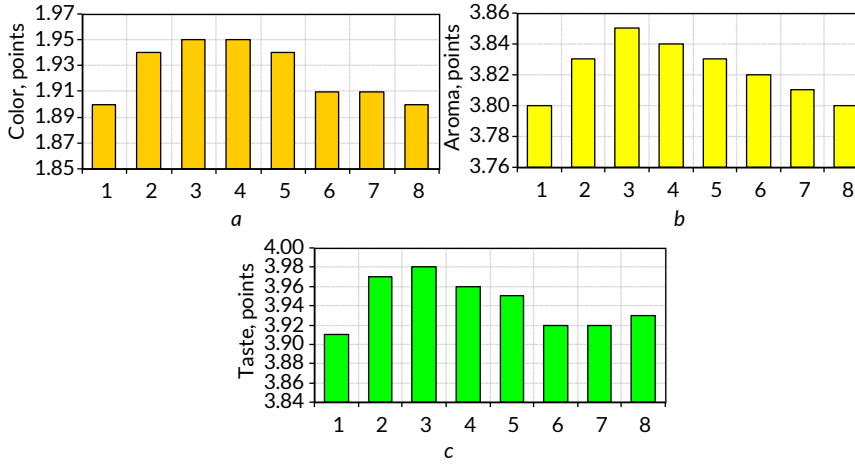
14.4.2 Organoleptic characteristics of water-alcohol infusions of tea-aromatic raw materials

The organoleptic evaluation of water-alcohol infusions of tea-aromatic raw materials (**Fig. 14.3, *c***) demonstrated a wide diversity in sensory parameters such as clarity and color (**Fig. 14.4, *a***), aroma (**Fig. 14.4, *b***), and taste (**Fig. 14.4, *c***), reflecting the botanical origin and chemical composition of each plant source. The sensory evaluation score (*S.e.*) ranged from 9.63 to 9.78 points, indicating a generally high level of acceptability across all samples.

The control sample (*S.e.* = 9.61) – a water-alcohol mixture – was colorless, had a pronounced alcoholic aroma, and a moderately burning, empty taste. In contrast, the infusion of mate was light brown in color with a woody aroma and a distinct sour-bitter taste accompanied by a long-lasting bitter aftertaste (*S.e.* = 9.74). The green tea infusion had a brownish-brown color, a fragrant tea-like aroma, and a sour-bitter, slightly astringent taste (*S.e.* = 9.78), receiving the highest overall score.

The red tea infusion was bright red, with a tea and spicy aroma and a characteristically bitter and astringent taste (*S.e.* = 9.75). The black tea infusion showed

a dark brown color, tea-woody aroma, and a moderately burning, strongly astringent taste (*S.e.* = 9.72), indicating the impact of full fermentation on flavor profile.



1 – water-alcohol mixture (control); 2 – water-alcohol infusion of mate;
3 – water-alcohol infusion of green tea; 4 – water-alcohol infusion of red tea;
5 – water-alcohol infusion of black tea; 6 – water-alcohol infusion of orange peel;
7 – water-alcohol infusion of mandarin peel; 8 – water-alcohol infusion of lemon peel

Fig. 14.4 Characteristics of water-alcohol infusions:
a – clarity and color; *b* – aroma; *c* – taste

Citrus peel infusions demonstrated milder sensory properties. The orange peel infusion was transparent with a light-yellow hue, had a faint alcoholic yet fresh aroma, and a mild, slightly sweet taste (*S.e.* = 9.65). The mandarin peel infusion exhibited a similar color and a mandarin-like aroma, with a gentle, sweet taste (*S.e.* = 9.64). The lemon peel infusion was pale yellow in color, with a faint lemon-like aroma and a mild, slightly sweet taste with distinctive lemon notes (*S.e.* = 9.63).

These results suggest that citrus peel infusions are organoleptically more delicate and potentially more acceptable for a wide range of consumers, while tea-based infusions, particularly green and red teas, offer more pronounced and complex flavor profiles with a higher antioxidant potential.

Water-alcohol infusions of tea-aromatic compositions based on Ilex paraguariensis are promising semi-finished products for restaurant technology, which, due to increased antioxidant properties, are able to slow down negative processes in the human body [3, 6, 19, 20] and improve the sensory evaluation of finished products.

14.4.3 Recommendations for technological application

Despite the high antioxidant activity demonstrated by citrus peel infusions, green tea received the highest sensory evaluation score (*S.e.* = 9.78 points), which is attributed to its well-balanced aroma and rich, astringent flavor profile. Mate also showed a high score (*S.e.* = 9.74 points); however, its long-lasting bitter aftertaste may limit its application at high concentrations in beverage formulations.

The orange peel infusion demonstrated the highest antioxidant parameters – RE_{inf} = 255.12 mV and RE_{plant} = 204.00 mV – combined with favorable organoleptic characteristics, making it particularly promising for the development of liqueurs and spirit-based beverages. Its mild, slightly sweet taste and fresh citrus aroma offer significant potential for enhancing the functional and sensory qualities of alcoholic drinks.

14.4.4 Creation of tea-aromatic compositions

Creation of tea-aromatic compositions based on *Camellia sinensis*, *Ilex paraguariensis* and *Citrus sinensis*. **Fig. 14.5** presents the results of a study on the influence of gradual replacement of green tea (*Camellia sinensis*) with yerba mate (*Ilex paraguariensis*) and the addition of orange peel (*Citrus sinensis*) on the physicochemical and sensory characteristics of water-alcohol infusions (**Fig. 14.6**).

The substitution experiment was conducted in six variants with increasing content of mate (from 0 to 100%) and corresponding decrease in green tea (from 100 to 0%). Orange peel was added at a constant level of 5% in intermediate blends (20–80% mate).

The pH values of the infusions decreased slightly with increasing mate content, indicating a moderate increase in acidity, with values ranging from 7.71 to 7.28 (**Fig. 14.5, *a***).

The calculated minimum redox potential (Eh_{min}) increased progressively from 178.18 mV to 196.35 mV, due to the shift in pH (**Fig. 14.5, *b***). The measured redox potential (Eh_{act}) also rose steadily with mate content, from 71.00 mV in the green tea variant to 84.00 mV in pure mate infusion (**Fig. 14.5, *c***).

The infusion redox effect (RE_{inf}) peaked at 115.15 mV (60% mate), suggesting that partial replacement with mate improves redox performance (**Fig. 14.5, *d***). The plant material contribution (RE_{plant}) to antioxidant capacity was highest at 64.03 mV (60% mate), indicating strong antioxidant potential of mate, especially in combination with orange peel (**Fig. 14.5, *e***).

Despite the increasing redox activity, the sensory evaluation (*S.e.*) remained consistently high across all samples, with scores between 9.74 and 9.82 points on a 10-point scale. The highest sensory score was recorded for the blend containing 20% mate, 75% green tea, and 5% orange peel, suggesting a balanced flavor and aroma profile.

These findings indicate that a combination of green tea, mate, and citrus peel can optimize both the antioxidant properties and sensory appeal of water-alcohol infusions, which is promising for the development of functional alcoholic beverages.

The addition of 5% citrus peel infusion to the blend of mate/green tea/orange peel at a ratio of $\omega = 20/75/5\%$ (**Fig. 14.5, *f***) significantly enhanced the sensory characteristics of the infusion (*S.e.* = 9.82 points). This modification reduced the intensity of bitterness and enriched the aromatic profile with fresh fruity notes, contributing positively to the overall evaluation of the water-alcohol infusion based on tea-aromatic raw materials (**Fig. 14.6**).

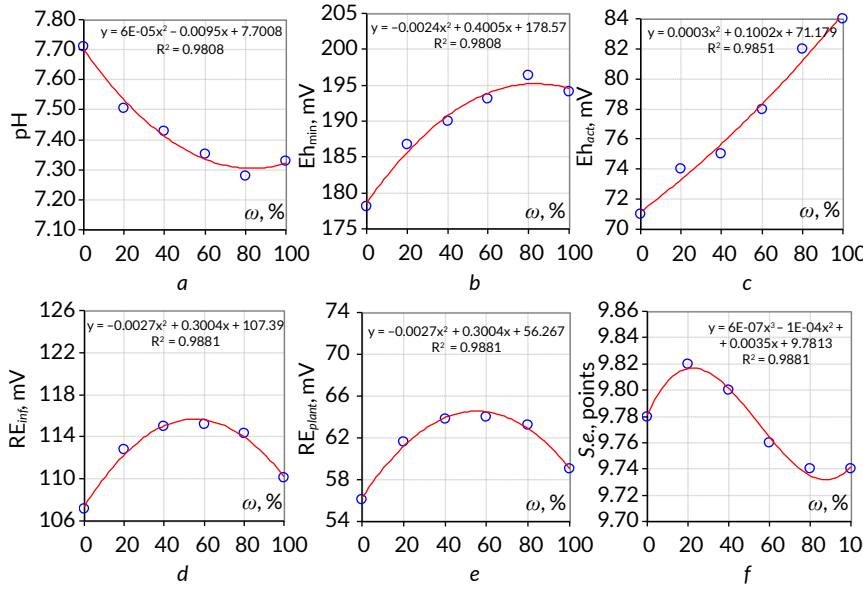


Fig. 14.5 Redox characteristics and sensory evaluation of water-alcohol infusions of tea-aromatic compositions as influenced by the mass fraction (ω) of mate, green tea and orange peel: *a* – active acidity (pH); *b* – the minimum theoretical value of RP (Eh_{min}); *c* – actual measured of RP (Eh_{act}); *d* – recovery energy of infusions (RE_{inf}); *e* – the energy of reduction/oxidation of vegetable raw materials (RE_{plant}); *f* – sensory evaluation indicators (*S.e.*)

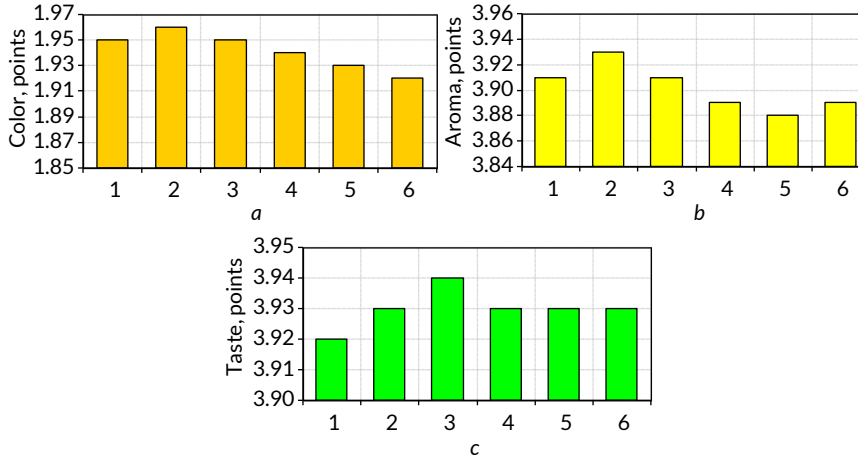


Fig. 14.6 Sensory evaluation of water-alcohol infusions of tea-aromatic compositions as influenced by the mass fraction (ω) of mate/green tea/orange peel: *a* – clarity and color; *b* – aroma; *c* – taste

Creation of tea-aromatic compositions based on *Camellia sinensis*, *Ilex paraguariensis* and *Citrus reticulate*. **Fig. 14.7**, **14.8** presents the physicochemical and sensory characteristics of water-alcohol infusions prepared using red tea (*Camellia sinensis*), yerba mate (*Ilex paraguariensis*), and mandarin peel (*Citrus reticulata*). The formulation involved six variants with a gradual increase in mate content (from 0 to 100%) and a corresponding decrease in red tea (from 100 to 0%). Additionally, 5% mandarin peel was included in the intermediate formulations containing 20–80% mate.

The pH level slightly decreased with the increase in mate content – from 7.45 (100% red tea) to a minimum of 7.26 (80% mate) – indicating a moderate increase in acidity due to the presence of mandarin peel (**Fig. 14.7, *a***). At 100% mate, the pH rose slightly to 7.33, possibly due to the absence of the more acidic mandarin peel.

The calculated minimum redox potential (Eh_{min}) increased from 189.10 mV to 197.10 mV with the rising proportion of mate up to 80%, which can be attributed to changes in the system's acidity (**Fig. 14.7, *b***). At 100% mate, Eh_{min} slightly decreased to 194.14 mV.

In contrast, the measured redox potential (Eh_{act}) decreased from 89.00 mV to 84.00 mV, indicating an increase in the reducing power of the infusions with higher mate content (**Fig. 14.7, *c***).

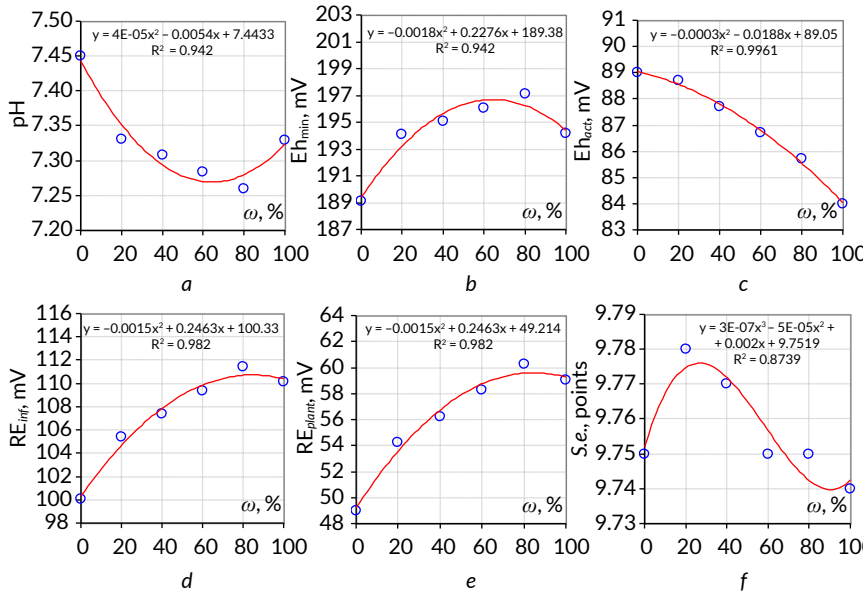


Fig. 14.7 Redox characteristics and sensory evaluation of water-alcohol infusions of tea-aromatic compositions as influenced by the mass fraction (ω) of mate, red tea and mandarin peel: *a* – active acidity (pH); *b* – the minimum theoretical value of RP (Eh_{min}); *c* – actual measured of RP (Eh_{act}); *d* – recovery energy of infusions (RE_{inf}); *e* – the energy of reduction/oxidation of vegetable raw materials (RE_{plant}); *f* – sensory evaluation indicators (*S.e.*)

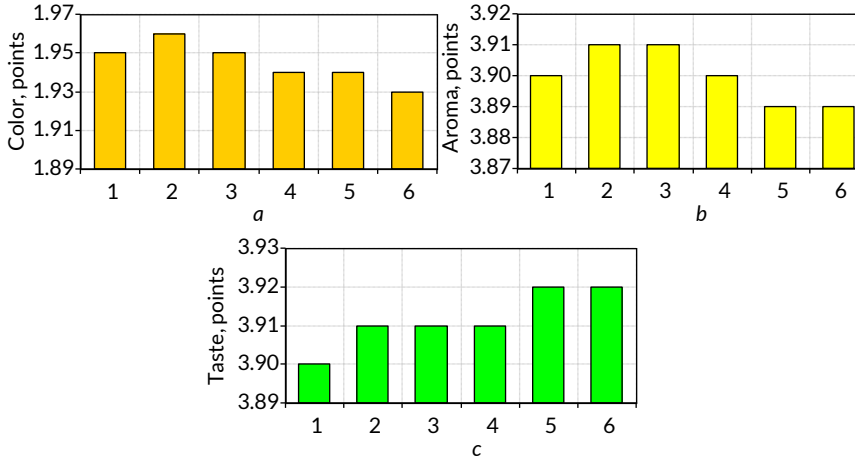
The redox effect of the infusion (RE_{inf}) increased with the addition of mate, reaching a maximum of 111.40 mV at 80% mate, and slightly declined thereafter (**Fig. 14.7, *d***). This suggests that yerba mate significantly contributes to the redox activity of the blend.

The contribution of plant materials to antioxidant capacity (RE_{plant}) followed a similar trend, increasing from 48.98 mV (red tea) to a peak of 60.28 mV (80% mate), confirming the strong antioxidant potential of yerba mate, particularly in combination with mandarin peel (**Fig. 14.7, *e***).

Sensory evaluation (*S.e.*) remained consistently high across all samples, ranging from 9.74 to 9.78 on a 10-point hedonic scale (**Fig. 14.7, *f***). The highest score of 9.78 was recorded for the blend containing 20% mate, 75% red tea, and 5% mandarin peel (ω = 20/75/5%), reflecting a balanced taste and aroma profile (**Fig. 14.8**).

This composition exhibited an exceptionally harmonious taste and aroma. Taste – well-balanced, featuring a soft bitterness from mate, mellowed by the sweet-floral

notes of red tea and citrus undertones from mandarin peel (**Fig. 14.8, *c***). A mild astringency, typical of semi-fermented tea, added depth without overwhelming the palate. Aroma – fresh and rich, with pronounced fruity-citrus nuances (**Fig. 14.8, *b***). Subtle essential oil notes from the mandarin peel created a delicate sweet base, while the red tea contributed warmth with its woody-honeyed accents. Mate provided a gentle herbal-grassy bouquet. Thanks to this balance, the infusion demonstrated high organoleptic integrity, a pleasant aftertaste, and an absence of sharp or dominant notes – qualities that are critical for the development of innovative functional beverages with strong market potential. Thus, the inclusion of yerba mate and mandarin peel into red tea-based infusions enhances antioxidant properties without compromising sensory appeal, making it a promising direction for the development of functional tea-aromatic drinks.



1 – ω = 0/100/0%; 2 – ω = 20/75/5%; 3 – ω = 40/55/5%;
4 – ω = 60/35/5%; 5 – ω = 80/15/5%; 6 – ω = 100/0/0%

Fig. 14.8 Sensory evaluation of water-alcohol infusions of tea-aromatic compositions as influenced by the mass fraction (ω) of mate, red tea and mandarin peel:
a – clarity and color; *b* – aroma; *c* – taste

Creation of tea-aromatic compositions based on *Camellia sinensis*, *Ilex paraguariensis* and *Citrus limon*. **Fig. 14.9**, **14.10** illustrates the physicochemical and sensory parameters of water-alcohol infusions composed of black tea (*Camellia sinensis*), yerba mate (*Ilex paraguariensis*), and lemon peel (*Citrus limon*). The formulations varied in the ratio of ingredients, increasing the proportion of mate from 0% to 100%, while

reducing black tea from 100% to 0%. In variants containing 20–80% mate, 5% lemon peel was additionally introduced.

pH values showed a gradual increase from 7.07 (100% black tea) to 7.33 (100% mate), indicating a decrease in acidity with higher mate content. Notably, pH increased more steadily in comparison to the red tea-based samples, possibly due to lower acidity contribution from lemon peel (**Fig. 14.9, *a***).

Minimum redox potential (Eh_{min}) decreased with rising mate content – from 205.46 mV to 194.14 mV – suggesting that the system becomes more reductive with increased mate presence (**Fig. 14.9, *b***).

Actual redox potential (Eh_{act}) significantly decreased from 127.00 mV (100% black tea) to 84.00 mV (100% mate), indicating a pronounced increase in reducing capacity of the infusion as mate replaces black tea (**Fig. 14.9, *c***).

Infusion redox effect (RE_{inf}) increased from 78.06 mV to 110.14 mV as mate content rose, confirming the active redox potential enhancement due to mate incorporation (**Fig. 14.9, *d***).

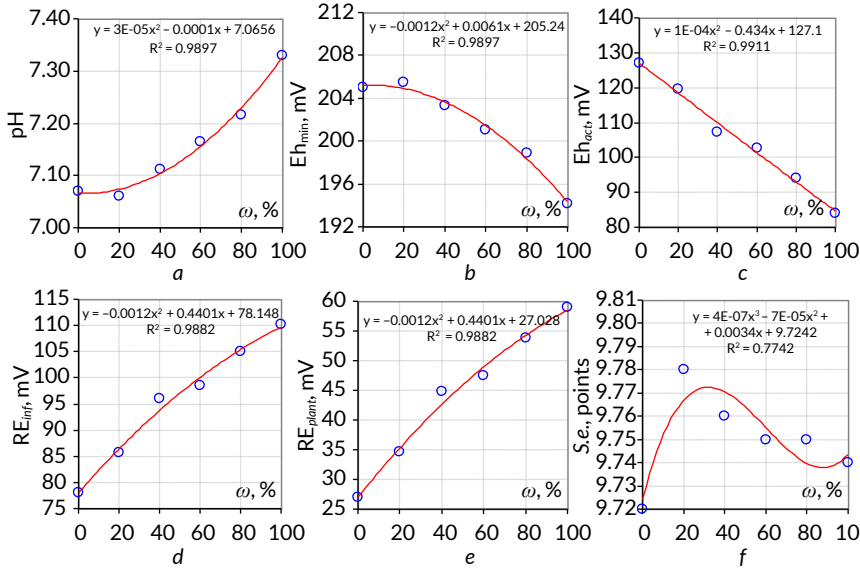


Fig. 14.9 Redox characteristics and sensory evaluation of water-alcohol infusions of tea-aromatic compositions as influenced by the mass fraction (ω) of mate, black tea and lemon peel: *a* – active acidity (pH); *b* – the minimum theoretical value of RP (Eh_{min}); *c* – actual measured of RP (Eh_{act}); *d* – recovery energy of infusions (RE_{inf}); *e* – the energy of reduction/oxidation of vegetable raw materials (RE_{plant}); *f* – sensory evaluation indicators (*S.e.*)

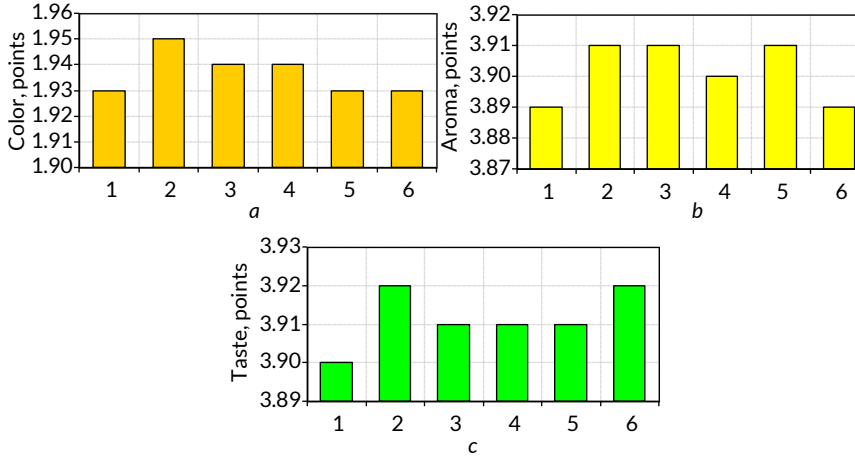
Plant-derived antioxidant potential (RE_{plant}) demonstrated a strong linear growth – from 26.94 mV at 100% black tea to a peak of 59.02 mV at 100% mate. This further affirms the significant antioxidant contribution of yerba mate, particularly in synergy with lemon peel (**Fig. 14.9, *e***).

Sensory evaluation (*S.e.*) scores remained high across all compositions, ranging from 9.72 to 9.78 points on a 10-point scale. The highest score of 9.78 was observed at 20% mate, 75% black tea, and 5% lemon peel (ω = 20/75/5%) (**Fig. 14.9, *f***). This composition offered an optimal balance of taste and aroma.

Taste-aroma profile. The sample with ω = 20/75/5% was especially notable for its well-rounded organoleptic properties.

Taste – smooth and structured, combining the robust body of black tea with the light herbal bitterness of mate (**Fig. 14.10, *c***). Citrus zest from lemon peel introduced freshness and slight tanginess that elevated the overall profile without overwhelming other notes.

Aroma – clean, bright, and refreshing (**Fig. 14.10, *b***). The essential oil components of lemon peel created an invigorating top note, while black tea contributed warm, malty undertones. Mate added a subtle vegetal-herbal character that enriched the aromatic complexity.



1 – ω = 0/100/0%; 2 – ω = 20/75/5%; 3 – ω = 40/55/5%;
4 – ω = 60/35/5%; 5 – ω = 80/15/5%; 6 – ω = 100/0/0%

Fig. 14.10 Sensory evaluation of water-alcohol infusions of tea-aromatic compositions as influenced by the mass fraction (ω) of mate, black tea and lemon peel:
a – clarity and color; *b* – aroma; *c* – taste

The overall result is a harmonious beverage with high antioxidant activity and excellent sensory integrity, ideal for the development of functional drinks with enhanced health benefits and appealing taste.

14.4.5 Innovative technology of functional beverages

Water-alcohol infusions serve as intermediate products widely used in the production of liqueurs, functional beverages, and therapeutic-prophylactic drinks. They are obtained through maceration (infusion) of plant-based raw materials – both aromatic (tea products, spices, aromatic herbs) and neutral – into a water-alcohol solution with an ethanol concentration ranging from 40% to 90%. The technological process is carried out in accordance with the relevant technological instructions and current regulatory standards, complying with state sanitary norms and food safety regulations.

Infusion, as a core extraction method, ensures the qualitative transfer of valuable compounds from raw materials into the solvent, while the presence of ethanol acts as a stabilizing agent. This approach not only prolongs the shelf life of the resulting infusions but also creates a stable matrix for the development of complex beverage compositions with a controlled impact on metabolic processes in the human body.

The extraction process is driven by diffusion, which is governed by the kinetic energy of molecules – gradual concentration equalization occurs between the solvent (water-alcohol mixture) and the soluble substances located in the plant cell structure. The efficiency of extracting bioactive compounds is influenced by several key factors: the degree of raw material grinding, the mass ratio of plant material to extractant volume, the ethanol concentration in the solvent, the number of maceration cycles (single or double), the duration of infusion, mixing frequency, and extraction temperature.

Under industrial conditions, the most rational approach is the two-stage maceration method carried out at a temperature of 18–25°C. This method involves soaking the raw tea-aromatic material in a water-alcohol mixture for 5 to 14 days, depending on the type of raw material, followed by separation of the first infusion, re-soaking (second maceration), and repeated extraction. After the process is completed, the two extracts are combined, while the remaining raw material is either disposed of or subjected to secondary alcohol evaporation to recover residual ethanol.

As a result of macerating tea-aromatic raw materials in a water-alcohol medium, a wide range of biologically active compounds is extracted: polyphenols (catechins, flavonoids), tannins, caffeine, organic acids, vitamins (B, C, P groups), minerals, and essential oils. Due to the high solubility of ethanol and its ability to preserve the

activity of components without oxidation, the final product exhibits stable antioxidant activity and has a significant effect on the redox balance of the body's internal environment. These properties make such infusions a promising bioactive base for the development of liqueurs, bitters, tinctures, and tonic beverages with targeted functional effects.

Thus, the optimization of maceration processes in water-alcohol systems opens up broad prospects for creating new types of alcoholic beverages with enhanced biological value, prolonged antioxidant action, and targeted modulation of redox processes in the human body. Technologically justified extraction and rational combination of formulation components not only preserve but also enhance the functional properties of the original plant material, contributing to the development of a new generation of functional beverages.

Based on the results of physicochemical and sensory evaluation studies of water-alcohol infusions prepared from tea-aromatic compositions, the optimal ratio was determined to be 20% mate, 75% tea (green, red, black), and 5% citrus peel (orange, mandarin, lemon) for further modeling of the functional alcoholic beverages of enhanced quality.

It was established that the mass ratio (ω = 20/75/5%) provides the highest sensory scores among all composition variants:

– or mate/green tea/orange peel – *S.e.* = 9.82 points;

– for mate/red tea/mandarin peel – *S.e.* = 9.78 points;

– for mate/black tea/lemon peel – *S.e.* = 9.78 points.

This result is due to the harmonious combination of taste and aromatic characteristics: the mild bitterness of mate is well-balanced by the sweet, floral notes of tea, while citrus peel adds freshness, lightness, and a fruity aroma. The indicated composition is considered promising for the development of functional beverages with antioxidant properties and high consumer appeal.

Formulation and blending of functional alcoholic beverages. Among liqueur and spirits products, fruit liqueurs (nalivkas) occupy a special place. These are alcoholic beverages with an alcohol content ranging from 15% to 35% and a total extract concentration of 15–50 g/100 cm^3. They are traditionally produced from fresh fruit raw materials or their semi-finished products, with the addition of various ingredients that define the taste, aroma, and functional properties of the final product.

To develop a liqueur with enhanced antioxidant properties and improved sensory characteristics, water-alcohol infusions based on tea-aromatic raw materials were used as the primary semi-finished ingredient. This approach allows the creation of a beverage that may help strengthen the immune system, improve metabolic processes, and positively affect cardiovascular function.

The formulation of the developed functional alcoholic beverage includes the following components (**Fig. 14.11**):

– water-alcohol infusion of a tea-aromatic composition (mate/tea/citrus zest in the mass ratio ω = 20/75/5%) – 38.49%;
– brandy – 7.54%;
– vanillin solution (1:10) – 0.01%;
– sugar syrup (65.8%) – 53.08%;
– citric acid – 0.28%;
– colorant ("caramel color") – 0.60%;
– ethanol and water – to adjust the final alcohol content to 20% vol.

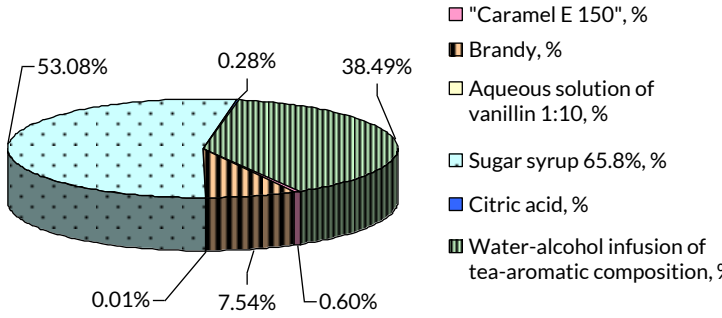


Fig. 14.11 Blending of alcoholic beverage

The proposed recipe enables the production of a functional alcoholic beverage with a balanced sensory profile and pronounced antioxidant activity. Through the synergistic combination of tea-aromatic infusions, brandy, and flavor-enhancing additives, the beverage acquires a smooth, pleasant flavor that aligns with contemporary trends in health-oriented drink production.

The diversity of alcoholic beverages is largely determined by the wide range of combinations possible between ethanol and natural ingredients. The use of tea-aromatic compositions in various proportions allows for the creation of novel flavor profiles while enriching the end product with bioactive properties [26, 33–36].

Such compositions not only enhance the organoleptic palette of the beverages but also contribute to their functional value. Of particular importance is their ability to modulate redox reactions in the human body, which can help reduce oxidative stress, regulate cellular metabolism, and support general homeostasis.

The developed tea-aromatic compositions provide a synergistic effect, resulting in a product with harmoniously balanced sensory properties and improved functional

characteristics. This approach opens new avenues for the development of innovative functional alcoholic beverages.

These beverages represent a new generation of functional products, created from natural extracts and infusions of high-quality plant-based raw materials. Their optimized composition ensures high antioxidant activity, effectively protecting the body from the harmful effects of free radicals and supporting overall health. The innovative ingredient selection guarantees not only beneficial health effects but also excellent flavor and aroma characteristics, meeting the growing demand for health-oriented alcoholic beverages.

14.5 Conclusions

The feasibility of using water-alcohol infusions of tea-herbal raw materials (*Ilex paraguariensis*, *Camellia sinensis*, *Citrus spp.*) for the production of alcoholic beverages has been substantiated. These components are characterized by high bioactivity, stability of polyphenolic compounds in alcoholic media, appealing aroma, and favorable sensory properties, making them an effective basis for innovative functional beverages.

The antioxidant activity of the obtained infusions has been determined. The highest reducing capacity (RE_{plant}) was observed in citrus peel infusions (up to 204.00 mV for orange peel), green tea (56.06 mV), and mate (59.02 mV). This indicates the presence of a significant amount of bioactive compounds that retain antioxidant potential in ethanol-containing systems.

The potential for modifying infusions based on tea-aromatic compositions within alcoholic beverage technology has been explored. It was established that the optimal mass ratio of components ω = 20/75/5% (mate/tea/citrus peel) provides a balanced flavor, reduces the bitterness of mate, enhances the aroma with fresh fruity notes, and increases the overall sensory evaluation (up to 9.82 points – for mate/green tea/orange peel).

Sensory evaluation of the infusions confirmed their suitability for commercial development. All infusions received high sensory scores (ranging from 9.63 to 9.82 on a 10-point scale), indicating strong consumer appeal and potential for implementation in the restaurant industry to produce innovative functional alcoholic beverages.

Optimized formulations for functional alcoholic beverages enriched with antioxidant tea-herbal infusions have been developed. The formulation includes: 38.49% of the infusion (mate/tea/citrus peel in a 20/75/5% ratio), 7.54% brandy, 53.08% sugar syrup, as well as flavoring agents and colorants. The alcohol content is adjusted to

20% vol., ensuring a balance between functionality, taste characteristics, and consumer appeal.

The integration of antioxidant-rich infusions based on *Ilex paraguariensis*, *Camellia sinensis*, and *Citrus spp.* into alcoholic beverage technology offers new opportunities for the restaurant industry to expand product offerings, enhance functional value, develop a positive brand image, and tap into the growing segment of health-conscious and innovative beverages.

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CHAPTER 15

Technology improvement of cooked sausage products with the addition of non-traditional raw materials

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Abstract

The growing interest in functional meat and fish-based foods has driven the development of novel formulations enriched with biologically active and nutritionally beneficial ingredients. This research explores the impact of incorporating unconventional components – such as chicken meat, spelt flour, dried vegetables, cuttlefish ink, and red caviar – into the composition of cooked fish sausages made primarily from hake. Three experimental formulations were created by substituting 10% of the fish meat with chicken and adding 6% spelt flour. Additionally, each variant included one of the following: bell pepper, olives, or garlic.

The study evaluated various parameters, including proximate composition (moisture, protein, fat, ash), water-holding and moisture-binding capacities, texture-related properties (shear stress), oxidative stability (acid and peroxide values), and sensory characteristics. Protein content in the modified products increased by 8–10% relative to the control (17.2 vs. 15.1 g/100 g). Among the samples, the first exhibited the highest water-holding capacity (86.3%), while the second and third demonstrated a notable 18–20% enhancement in structural density.

Over a 10-day refrigerated storage period, the third sample maintained superior oxidative stability, as its acid value increased only slightly (from 1.7 to 2.3 mg KOH/g fat). Sensory evaluation revealed improved acceptability: Sample 1 achieved a score of 4.6, and Sample 3 received 4.5, both outperforming the control 3.8.

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Overall, the integration of chicken meat, spelt flour, and dried vegetable inclusions into fish sausage formulations resulted in improved nutritional quality, functional-technological performance, and organoleptic appeal. These findings support the potential use of alternative raw materials in the production of value-added, health-oriented fish sausages. Further research is recommended to assess microbial stability over extended storage periods and to determine consumer preferences for potential market introduction.

Keywords

Hake, vegetable raw materials, cuttlefish ink, red caviar, sausage products.

15.1 Introduction

In recent years, a new direction in the food industry has been widely recognized all over the world – the so-called functional nutrition, which refers to the use of such products of natural origin, which, when used systematically, have a regulatory effect on the human body.

At the same time, the analysis of domestic and foreign literature shows that today little attention is paid to the development of technologies for specialized food products with targeted physiological and biochemical properties, increased nutritional and biological value. Therefore, the development of technologies for combined fish products (cooked sausage products) for functional nutrition is an important and relevant direction of scientific research.

The production of fish sausages has been successfully developed in many countries over the past few years. This started in Japan. The expansion of this production is stimulated by an increase in the catch of small fish and fish with low palatability, which can be successfully used to produce fish sausage products [1, 2].

Moreover, as experts note, fish sausage is more useful for human health than its meat and chicken counterparts due to the saturation of easily digestible protein and essential amino acids, such as lysine and tryptophan. Another advantage of fish sausage is that, with the initial raw materials, it is possible to establish its production at a specialized fish factory and a regular meat processing plant.

The technology for producing sausage products has been developed and implemented in many countries, but production in Ukraine remains limited.

Fish and fish processing products have traditionally been essential in the human diet due to their high nutritional value and remarkably complete animal protein, vitamins, and macro and microelements [3]. In modern conditions, there is an increasing interest in developing new types of fish products, including those with

functional purposes, which contribute to maintaining public health and ensuring high-quality nutrition.

A separate niche in the food market is occupied by fish sausages – an innovative product that can serve as an alternative to traditional meat. The technology of their production involves the use of minced fish combined with components that improve structural-mechanical and organoleptic properties: lard, eggs, dry milk, starch, spices, salt, stabilizers, and food additives (such as phosphates, nitrites, etc.) [4].

Among the current directions in improving meat product technologies, special attention is given to using mineral components to enhance their nutritional value. In the study by I. Shurduk et al. [5], the feasibility of using a protein-mineral supplement (PMS) as a source of calcium in the formulations of emulsion-type meat products was substantiated. According to the study results, adding 7–8% PMS has a positive effect on the water-binding, fat-retention, and emulsifying properties, as well as the structure of the meat system. Improved microbiological stability and sensory characteristics of the final product were also observed, without negatively affecting its taste. The authors particularly emphasize that more than 60% of the calcium in the final product is present in the form of organically bound compounds, ensuring a high degree of absorption. The proposed technology enables the creation of functional meat products with enhanced biological value and health-promoting effects.

O. Shtonda [6] developed recipes of combined meat-vegetable and fish-vegetable cooked sausage products with the taste and smoke aroma using CO_2 extract of the smoke liquid. In this work, the effect of added plant components (carrots, eggplants, onions and peas in meat-vegetable sausages, carrots, eggplants, onions and peas, in fish-vegetable sausages – carrots, potatoes, onions and rice) on the nutritional properties of the product, the yield of the finished product and determination of the sanitary and hygienic properties of the finished product due to the use of CO_2 smoke extract.

X. Zhao et al. [7] investigated the possibility of using such non-traditional additives as a structuring agent from fish skin, lotus seeds, water, and water-alcohol infusions from Sargentodoxa cuneata (Sargentodoxa cuneata Rend. et Wils) in the technology of making fish sausages, which made it possible to obtain sausages with high organoleptic indicators.

N. Bozhko et al. [8] investigated the possibility of using squid and shrimp to produce cooked sausages. The study demonstrated that incorporating these seafood ingredients enhances the nutritional value and taste of the final product. Along with other authors, he investigated using protein-containing raw materials, such as soy protein, to produce boiled-smoked sausages. The use of such additives

allows for reducing the production cost and improving the nutritional value of the product [9].

O. Fursik [10], in her dissertation, substantiated the feasibility of using protein-containing functional compositions that include both plant and animal proteins to improve cooked sausage technology. Using such compositions makes it possible to enhanceenables the enhancement of the amino acid profile and the functional and technological properties of the product.

I. Martyniuk [11] investigated the possibility of using amaranth as an unconventional plant-based raw material to produce cooked sausages. The results showed that the addition of amaranth improves the organoleptic, physicochemical, and microbiological properties of the product.

Other authors, M. Paska and I. Markovych, investigated the use of lentil plant material and lentil flour in the technology of cooked sausages. They found that the addition of lentil flour improves the structure and consistency of sausage, as well as reduces production costs [12].

Other studies have been conducted using protein compositions that include both plant and animal proteins to improve cooked sausage technology. These compositions allow for the enhancement of the amino acid profile and the functional and technological properties of the product [13].

One of the promising raw materials for producing such products is African catfish (*Clarias gariepinus*), which is characterized by rapid growth rates, efficient feed conversion, low maintenance requirements, and high nutritional value of its meat. According to literature sources, African catfish meat contains, on average, 75% moisture, 16.9% protein, and 6.7% fat. In comparison, 100 g of the product provides over 40% of the daily selenium requirement and more than 20% of the phosphorus requirement. Studies on the water-holding capacity of the raw material indicate that African catfish meat can ensure a stable sausage mince structure, juiciness, and a tender texture in the final products [14].

The article by V. Tyshchenko et al. [15] discusses using fish mince as a raw material for sausage production. The study demonstrated that fish mince exhibits high functional and technological properties, enabling the production of high-quality and nutritious products.

The study by A. Tayeva et al. [16] investigates the potential for enhancing the functional and technological properties of cooked sausages by incorporating camel fat and chicken fillet. The effect of pumpkin shell powder on lipid oxidation and the functional and technological properties of sausages made from mixed meat was investigated. It was found that adding pumpkin shell powder enhances the taste and organoleptic characteristics of the product.

K. Elavarasan et al. explore the possibility of using millet and coconut flour to formulate fish sausages in their research. It was found that adding millet flour is an ideal healthy substitute for traditional wheat flour [17–19].

Critical studies have been conducted on incorporating textured soy protein (TSP) into surimi products, particularly fish sausages. It was found that adding 15% TSP improves gel strength, water-holding capacity, and organoleptic properties of the product while maintaining its quality for up to 120 days when stored at −18°C [19–21].

Critical studies have been conducted on incorporating textured soy protein (TSP) into surimi products, particularly fish sausages. It was found that adding 15% TSP improves gel strength, water-holding capacity, and organoleptic properties of the product while maintaining its quality for up to 120 days when stored at −18°C [18].

The analysis of scientific research suggests a high potential for enhancing the technology of cooked fish sausages using unconventional raw materials. Including components such as pumpkin shell powder, millet flour, textured soy protein, camel fat, and fish milt enhances the products' functional and technological properties. In particular, improvements have been observed in texture, gel strength, water-holding capacity, and the organoleptic characteristics of the sausages.

Moreover, using unconventional raw materials increases the biological value of the products by boosting the content of high-quality protein and beneficial fats, while also extending shelf life through the reduction of lipid oxidation. A significant advantage is the economic feasibility and environmental sustainability of these innovations, aligning with current trends in the development of the food industry.

Therefore, integrating unconventional raw materials into the production of cooked fish sausages effectively improves product quality and competitiveness while meeting the demands of healthy nutrition and sustainable development.

At the same time, the nutritional and biological value. Therefore, developing technologies for combined fish products (cooked sausage products) for functional nutrition is an essential and relevant direction of scientific research.

15.2 Characteristics of the nutritional and biological value of fish and meat raw materials

The primary raw materials for the production of cooked sausage products are minced hake (in a frozen state) and chicken fillet (in a chilled state). According to organoleptic indicators, frozen fillet must meet the requirements and standards specified in **Table 15.1**.

Table 15.1 Organoleptic characteristics of frozen fish fillets

Indicator name	Characteristic and standard
Appearance: blocks individually frozen fillets	Clean, dense, with a flat surface without significant differences in block height. Clean, even, whole, without significant deformation. May exhibit: slight loosening of the muscle tissue along the edge of the fillet block; presence of scale residues on the surface of the fillet with skin without scales; skin damage in horse mackerel and sturgeon fillets at the sites where scutes have been removed
Placement procedure	The fillets are placed into molds in uniform layers: in the bottom layer with the skin or subcutaneous side facing downward, and in the top layer with the skin or subcutaneous side facing upward
Flesh consistency: after defrosting	Firm, typical of this type of fish
After boiling	Tender, juicy, brittle, typical of this type of fish. It may be slightly dry, fibrous, but not hard, rubbery, jelly-like
Flesh color	Typical of this type of fish
Odor (after defrosting)	Typical of fresh fish, without any foreign odor
Taste and smell after cooking	Typical for this type of fish, without any foreign taste or smell

The primary raw materials for cooking sausage products are minced hake (in a frozen state) and chicken fillet (in a cooled state).

The size and mass characteristics of fish are an important criterion for assessing its biological condition, marketable quality and technological suitability.

The aim of the study was to establish the average indicators of length, body weight, carcass weight, head, viscera, skin and scales, which allows for a reasonable assessment of the yield of finished products and the efficiency of raw material use.

The dimensional composition of the fish is given in the **Table 15.2**.

Table 15.2 Dimensional composition of hake

L_a, cm	L_i, cm	L_h, cm	L_t, cm	L_m, cm	h, cm	b, cm
–	–	–	–	25.2	6	4

Note: initial weight of gutted carcass – 356 g

The length of the carcass is 25.2 cm, the height of the fish body is 6 cm, and the width of the fish body is 4 cm (average size of the fish). The mass composition of hake is presented in **Table 15.3**.

Table 15.3 Mass composition of hake, %

Weight, kg	Content to the total weight of fish, %				
	fillet	skin	bones	fins	scales
0.356	82 ± 1.9	5.3 ± 0.3	7.57 ± 0.9	0.76 ± 0.3	0.03 ± 0.01

Note: initial weight of gutted carcass – 356 g; n = 5, p ≤ 0.05

The data obtained are the starting point for further physicochemical, technological and organoleptic studies, as well as for comparative analysis between different types of fish raw materials.

The output of fish meat is 301.3 g, waste – 48.4 g, losses – 6.3 g. The chemical composition of fish raw materials was determined during the study, as shown in **Table 15.4**.

Chicken provides moderate energy and contains highly digestible proteins with low collagen, offering good nutritional quality. It is also a source of unsaturated fats, primarily in the skin, which can be easily removed, and B vitamins such as pantothenic acid and thiamine. Consumption of chicken is associated with a lower risk of overweight and obesity, as well as cardiovascular diseases and type 2 diabetes. The chemical composition of chicken is given in **Table 15.5**.

Table 15.4 Chemical composition of hake, %

Indicator	Content
Protein content	18.31 ± 0.6
Fat content	1.31 ± 0.22
Moisture content	78.9 ± 2.83
Mineral content	1.48 ± 0.15

Note: n = 5, p ≤ 0.05

Table 15.5 Chemical composition of chicken, %

Indicator	Content
Calories, kcal	202 ± 4.0
Protein content	18.5 ± 0.17
Fat content	14.3 ± 0.21
Moisture content	3.7 ± 1.26
Mineral content	70.9 ± 2.25

Note: n = 5, p ≤ 0.05

The combination of fish and meat raw materials enables the production of a new, fully developed product, specifically a cooked sausage, utilizing various types of raw materials.

The nutritional value of salmon roe used for the production of cooked sausage products is given in **Table 15.6** [17].

Table 15.6 Nutritional value of salmon roe

Indicator	Content per 100 g of product
Calories, kcal	249
Protein, g	26.0
Fat, g	13.2
Water, g	62.0
Carbohydrate, g	1
B_1, μg%	1800
B_2, μg%	2100
Folic Acid, μg%	1300
PP, μg%	2.1
Pantothenic Acid, μg%	1.3
Vitamin C, μg%	93

Salmon caviar is a highly nutritious product with a significant biological value. 100 g of the product contains 249 kcal, which indicates its energy saturation. Caviar is rich in proteins (26.0 g), which makes it a valuable source of easily digestible amino acids necessary for maintaining muscle mass and cellular metabolism. The fat component (13.2 g) provides the body with beneficial fatty acids that play a key role in the functioning of the nervous and cardiovascular systems.

The high content of B vitamins (in particular B_1 – 1800 mcg%, B_2 – 2100 mcg%, folic acid – 1300 mcg%) contributes to the normalization of metabolism, maintenance of nervous system functions and hematopoiesis processes. Caviar also contains vitamin C (93 mcg%), which is an antioxidant and supports immunity.

Given these indicators, salmon caviar can be considered a functional product that combines high nutritional value, vitamin richness, and health benefits when consumed in moderation.

Given the limited data on the chemical composition of spelled flour grown in Ukraine, it is possible to investigate the composition of this flour (**Table 15.7**).

Spelt is notable for its high protein content. Research has shown that spelt contains 28% more protein, 1.6 times more fat, and 22% more minerals (ash) than

common wheat. Additionally, it has 7.6% fewer carbohydrates overall, including 20% less starch. While the total dietary fiber content in spelt is higher than in wheat, it contains less crude fiber.

Table 15.7 Chemical composition of spelled flour, % on dry matter

Indicator	Spelled flour
Protein, g	17.46
Fat, g	3.17
Carbohydrate, g	75.92
Includes Starch, g	52.49
Total Sugars, g	3.62
Dietary Fiber, g	14.34
Includes Roughage, g	2.1

The advantages of adding spelt flour to sausages: increased protein value, enrichment with dietary fiber, improved structure and water-binding properties, reduced starch content, improved mineral composition.

Therefore, adding spelt flour to sausage recipes allows to create functional products with improved nutritional properties, increase their dietary appeal and meet the needs of consumers focused on healthy eating.

Cuttlefish ink is a natural coloring agent that provides a deep black hue and comes in a convenient single-use package containing two 4 g sachets. Its composition includes: cuttlefish ink (40%), water, salt, and sodium carboxymethylcellulose stabilizer. It is gluten-free but may contain shellfish and traces of crustaceans, celery, and milk.

Cuttlefish ink is increasingly valued in the food industry not only for its natural pigmentation but also for its content of bioactive substances that may offer health-promoting effects. M. Gómez-Guillén et al. [22] noted that this ingredient contains melanin, peptides, and amino acids that contribute antioxidant, antimicrobial, and anti-inflammatory activities. These properties position cuttlefish ink as a multifunctional additive that supports visual enhancement and improved functional attributes of food products.

Incorporating natural colorants, such as cuttlefish ink, aligns with the modern trend toward clean-label ingredients and the increasing consumer preference for natural alternatives to synthetic additives [23]. In contrast to artificial colorants, it is considered a safer and more consumer-friendly option.

In addition, the intense black color and distinct flavor profile of cuttlefish ink make it a novel and appealing component in formulating premium and health-oriented foods, including fish-based sausages and alternative meat products [24]. Its use in cooked sausages made from unconventional raw materials is justified from a technological standpoint, as it improves product appearance, enriches flavor, and supports innovation in food development.

15.3 Recipes for cooked sausage products with the addition of non-traditional raw materials

Samples from the manufacturer Savin Product were used to produce cooked sausage products made from non-traditional raw materials. The recipe of the control sample is presented in **Table 15.8**.

Table 15.8 Sausage recipe Squid ink & Red roe and meat turkey, from the manufacturer Savin product

Components name	Prescription composition of the control sample, g/100 g of product
Turkey meat	48.3
Refined sunflower oil	28
Red caviar	6.5
Cow's powdered milk	6
Kitchen salt	1.3
Sugar	0.4
Spice extracts (nutmeg, black pepper, allspice)	0.5
Color fixative: sodium nitrite	0.008
Drinking water	8.492
Cuttlefish ink	0.5

In the formulated recipes for cooked sausage products, various vegetable ingredients were incorporated to enhance flavor characteristics, while the inclusion of natural color sources aimed to achieve a more visually appealing final product. Additionally, fish-based raw materials and modifications to animal-based components were incorporated to enhance taste and better align with daily nutritional needs. A novel water-binding agent was also introduced to enhance product stability and maintain shape. The finalized cooked sausage formulations are detailed in **Table 15.9**.

Table 15.9 Sausage recipes Squid ink & Red caviar and bell pepper, Squid ink & Red caviar and olives, Ink Cuttlefish & Red Caviar & Garlic

The name of the components	Recipe composition, g/100 g of products		
	Sample 1	Sample 2	Sample 3
Hake meat	42	47	45
Chicken meat	10	10	10
Refined sunflower oil	20.5	20.5	20.5
Red caviar	6.5	6.5	6.5
Potato starch	2	2	2
Spelled flour	6	6	6
Kitchen salt	1	1	1
Sugar	0.4	0.4	0.4
Spices (basil, oregano, thyme)	5.55	3.55	5.55
Cuttlefish ink	1.05	1.05	1.05
Dried Bulgarian red pepper	5	–	–
Dried olives	–	2	–
Dried garlic (granulated)	–	–	2

The development of formulations for cooked sausages incorporating plant-based raw materials, natural colorants, unconventional types of meat, and water-retaining components aligns with current trends in the food industry, which aim to improve product quality, safety, and functional properties.

According to I. Markovych research [24], the use of plant components, particularly lentil flour, contributes to the improved structure and consistency of sausage products while also helping to reduce production costs. The addition of natural colorants, such as cuttlefish ink, not only provides a rich color but also imparts antioxidant properties, as noted by M. Gómez-Guillén et al. [21], which positively affect product stability during storage.

Including fish raw materials in the formulations of cooked sausages enhances the nutritional value of the product due to its high content of complete proteins, polyunsaturated fatty acids, and minerals, as confirmed by the research of N. Bozhko et al. [8]. Replacing traditional meat ingredients with more easily digestible protein sources (e.g., African catfish or poultry meat) allows products to be better adapted to the needs of modern consumers, particularly those who follow healthy eating habits [26–28].

Additionally, incorporating water-retaining components, such as dietary fiber or stabilizers, enhances the texture, juiciness, and shape of the finished product. This is consistent with the findings of I. Shurduk et al. [5], who highlight the effectiveness of protein-mineral additives in enhancing the technological properties of emulsion-type meat systems.

Thus, comprehensive improvement of formulations by incorporating unconventional ingredients and enhanced structural components is a justified step toward developing cooked sausages with increased nutritional and functional value.

The obtained samples of cooked sausage products are shown in **Fig. 15.1–15.3**.

Fig. 15.1 Squid ink & red caviar & bell pepper (Sample 1)

Fig. 15.2 Cutball ink & red caviar & olives (Sample 2)

Fig. 15.3 Squid ink & red caviar & garlic (Sample 3)

Thus, by developing the aforementioned recipes, it is possible to obtain a cooked sausage product enriched with B-group vitamins, vitamin PP, vitamin A, and vitamin E, as well as mineral elements such as iron, iodine, phosphorus, calcium, and essential Omega-3 fatty acids. This product is easily digestible and aligns with the principles of healthy nutrition.

15.4 Properties of mince for the production of cooked sausage products

To assess the use of dried plant raw materials and to determine the optimal amount of additives in the production of cooked sausage products containing non-traditional raw materials, a study was conducted on the properties of the added components within a multi-component system, as the structure, composition, and production conditions of the final product directly depend on the properties of the mince. Indicators such as water-retaining capacity (WRC) and water-binding capacity (WBC) of the experimental mince affect the juiciness, density of the products, and the yield of the finished product. Results of the study of the WRC (**Fig. 15.4**) and WBC (**Fig. 15.5**) of the mince.

The influence of functional food additives on the technological characteristics of cooked sausage products is given in **Table 15.10**.

According to the data obtained, an increase in the mass of the sausage is observed after cooking. This is due to the swelling of dried plant components as a result of moisture release during the boiling-down process of the combined meat and fish raw materials, which constitute the main part of the product – the mince.

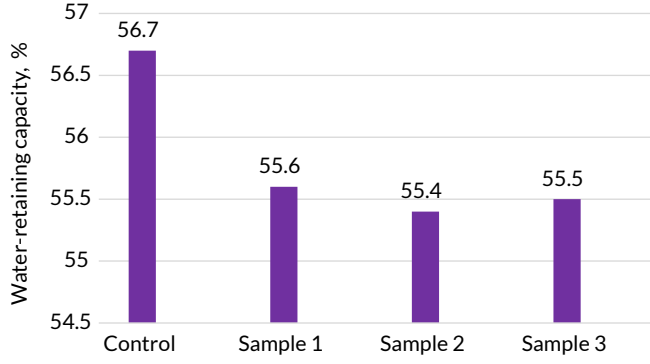

Fig. 15.4 Changes in the water-retaining capacity of mince

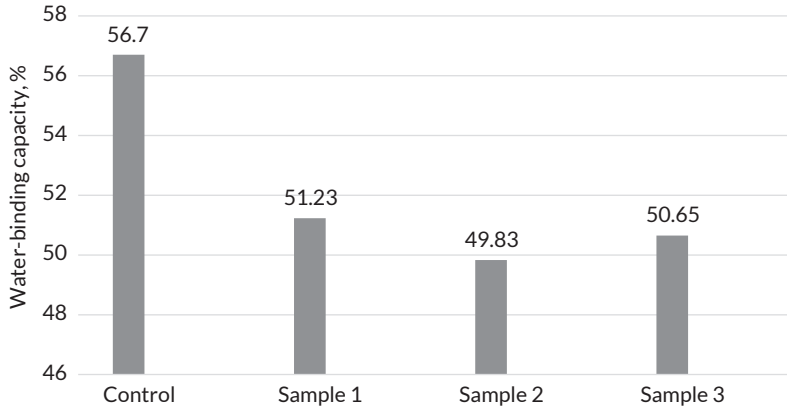

Fig. 15.5 Changes in the water-binding capacity of mince

Table 15.10 The influence of functional food additives on the technological characteristics of cooked sausage products

Sample	Mass of sausage prior to boiling, g	Mass of sausage after boiling, g
Sample 1	57.0942	59.7426
Sample 2	61.2023	62.8742
Sample 3	55.3214	56.1327

Based on the data presented in **Table 15.10**, it can be concluded that functional food additives have a positive effect on the technological characteristics of cooked sausage products, in particular, on the preservation or even increase in mass after heat treatment.

All three samples demonstrate an increase in the mass of sausages after boiling, which is an important indicator of technological efficiency and economic feasibility of using functional ingredients. In particular:

– Sample 1: the mass before boiling was 57.09 g, after boiling – 59.74 g, which indicates an increase of 2.65 g, or about 4.64%;

– Sample 2: mass before boiling – 61.20 g, after – 62.87 g, the increase was 1.67 g (≈ 2.73%);

– Sample 3: the mass increased from 55.32 g to 56.13 g, i.e. by 0.81 g (≈ 1.46%).

The greatest increase in mass after boiling is observed in Sample 1, the smallest in Sample 3, which may be due to both differences in the recipe and the properties of the functional additives used.

The increase in mass after boiling is attributed to the swelling of functional food components, including dried plant components that actively bind moisture. This is also partly due to the reduction of losses during heat treatment, resulting from the formation of a stable gel-like matrix that retains moisture within the product. In addition, the combination of meat and fish raw materials provides a balanced protein-fat structure of the mince, which enhances moisture retention during cooking.

Thus, the presented data confirm that the use of functional additives allows not only to increase the nutritional value of sausage products, but also to improve their technological properties, in particular, water-holding capacity water-retaining capacity and mass stability after heat treatment, which is an important factor in the production of quality products.

15.5 Research on the organoleptic evaluation of cooked sausage products

The tasting evaluation of vegetarian ice cream was carried out with the involvement of specialists with experience in the field of food technology. 5 people aged 25 to 45 years were selected as tasters, who had higher education in the field of food technology and experience in evaluating the organoleptic properties of food products for at least 3 years.

Before the start of the study, the tasters underwent a brief briefing, which included familiarization with the method of organoleptic evaluation on a five-point scale according to ISO 11036:1994, as well as a repetition of the criteria for evaluating appearance, taste, consistency, color and aroma.

In order to ensure the objectivity of the results, the tasting was carried out by blind evaluation, without prior informing the tasters about the composition or origin of the samples.

A quantitative evaluation of the cooked sausage products was conducted using a set of organoleptic indicators, comparing them to the control sample. Based on the overall organoleptic assessment, experimental formulations No. 1 and No. 3 demonstrated superiority over the control, which exhibited a very dense texture and an unpleasant taste with no distinct sausage flavor.

In formulation No. 1, the taste, aroma, and juiciness were enhanced by adding red bell pepper, which increases juiciness and imparts a pleasant sweet flavor due to its high moisture content. In formulation No. 3, the flavor profile was enhanced by incorporating dried garlic, resulting in a subtle and mild taste. Although formulation No. 2 scored lower overall compared to No. 1 and No. 3, it still outperformed

the control sample due to the inclusion of dried olives and herbs, which enhanced the texture and added a distinctive aroma.

To determine the qualitative differences in the organoleptic evaluation of the developed product, the construction of profilograms was added, allowing for the visual demonstration of the complete picture of the comparative assessment of the samples. The graphically obtained indicators are presented in **Fig. 15.6–15.8**.

Summarizing the results of the comparative evaluation of organoleptic properties, it can be concluded that adding plant-based raw materials enhances these sensory attributes. All developed formulations received higher overall scores than the control sample, although each showed improvements in specific indicators depending on the type of plant material used.

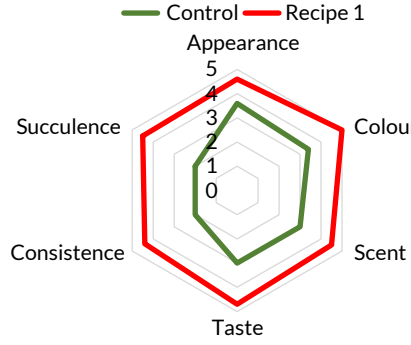

Fig. 15.6 Comparative analysis of Sample 1 with the control sample

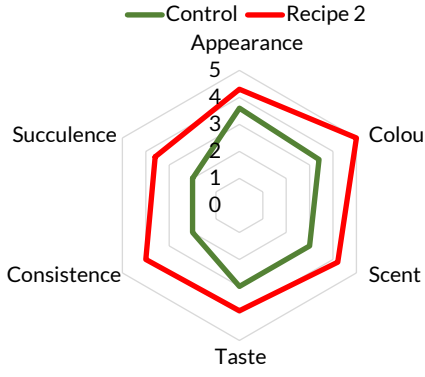

Fig. 15.7 Comparative analysis of Sample 2 with the control sample

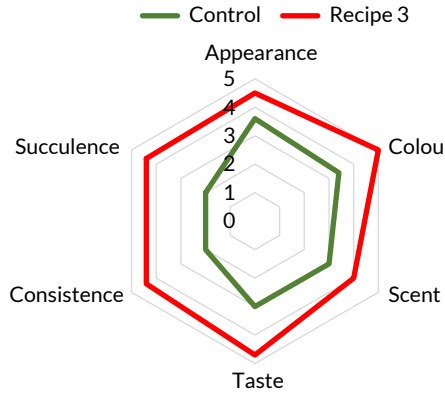

Fig. 15.8 Comparative analysis of Sample 3 with the control sample

The addition of plant-based raw materials to meat and fish products is an effective way to enhance the organoleptic properties of these products. According to the research by I. Markovych [24], soy protein in sausage formulations contributes to enhanced texture, taste, and overall consumer perception of the product. Similarly, the findings of showed that the inclusion of amaranth in cooked sausages increases their organoleptic appeal, as evidenced by higher ratings for flavor, aroma, and consistency [29–35]. Furthermore, the study by I. Bayram et al. [36–39] demonstrates that using pumpkin peel powder in sausage products significantly improves taste and textural characteristics, positively influencing the end consumer's perception of the product.

15.6 Research on structural and mechanical properties and chemical composition of cooked sausage products

Due to the incorporation of fish and additional plant raw materials in dried form (in particular, in the form of pieces, granulated spice particles) into the recipes of boiled sausages, a study was carried out on the influence of new ingredients on the consistency characteristics of the finished product. In order to quantitatively determine changes in the structure of the studied samples, the penetration method was used, which enables the evaluation of the density and elasticity of the product.

Spot samples were taken from one batch of mince at three different points, with a total mass of at least 250 g. A composite sample was used for measurement.

The sample was placed in a container after removing air by tapping the bottom and sealing with a spatula. After that, the container with the sample was kept in a water bath at a temperature of 20°C until the temperature equilibrium within 20 ± 5°C was reached. Temperature control was provided using a thermometer.

The indenter penetration depth was determined for ready-made boiled sausages, which are characterized by a firm-elastic consistency. For this purpose, a needle indenter weighing 2 g was used. Measurements were performed on the open surface of the sample, no closer than 10 mm to the edge and at the maximum distance from the places of previous punctures. In this case, zones with air inclusions, visible defects or inhomogeneous structure were avoided, which could affect the objectivity of the results.

When using a needle indenter, measurements were made at five points along the length of the product for each sample. In **Fig. 15.9**, the results of the ultimate shear stress for cooked sausage products are given.

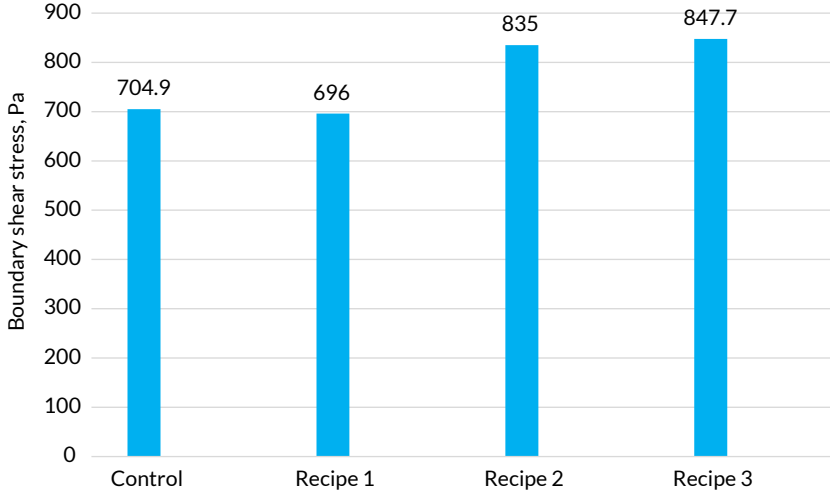

Fig. 15.9 Boundary shear stress of cooked sausage products

According to the diagram, Samples 2 and 3 exhibited statistically significant improvements in structural and mechanical properties ($p < 0.05$), with shear force values increased by 18–20% compared to the control, which can be attributed to the increased content of fish raw materials (an increase of 5 g in Sample 2 and 3 g in Sample 3) and variations in the ratio of spices to dried vegetable raw materials.

Although the amount of dried vegetable raw materials was the same in both samples (2 g each), Sample 2 contained a reduced quantity of spices compared to Sample 3.

Relative to the control sample, the density of Samples 2 and 3 increased by 18–20%. This improvement was due to the substitution of the binding agent, replacing powdered milk with a mixture of potato starch and spelled flour in a 2:6 ratio, and the incorporation of smaller pieces of plant material compared to Sample 1.

The study of the plasticity of the product was conducted using a method based on the separation of moisture from the sample during pressing by a load weighing 1 kg, sorption of the separated water by filter paper and determination of the released moisture by the size of the spot area formed on the paper. The results obtained are presented in **Fig. 15.10**.

Based on the data presented in the diagram, it can be concluded that the plasticity of the test samples differs significantly from that of the control. The plasticity of Samples 1 and 2 remains almost unchanged, but the plasticity of Sample 3 is 2 times less than the previous samples. This is due to the different types and sizes of plant raw materials introduced (Sample 1 – dried sweet pepper in pieces 6 × 6 mm; Sample 2 – dried olives in pieces 3 × 3 mm; Sample 3 – granulated garlic 8 × 16 mm).

In laboratory conditions, chemical composition studies were conducted to evaluate the quality of ready-made cooked sausage products from non-traditional raw materials. The comparative characteristics of the chemical composition depending on the introduced auxiliary raw materials are presented in **Fig. 15.11–15.13**.

The obtained results indicate that the developed formulations contain a lower protein level due to the partial substitution of fish raw materials with plant-based ingredients, a reduced fat content across all samples, and a higher mineral content compared to the control sample.

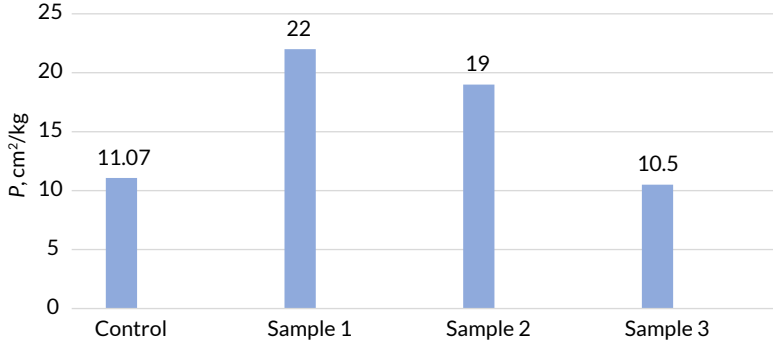

Fig. 15.10 Plasticity of cooked sausage products

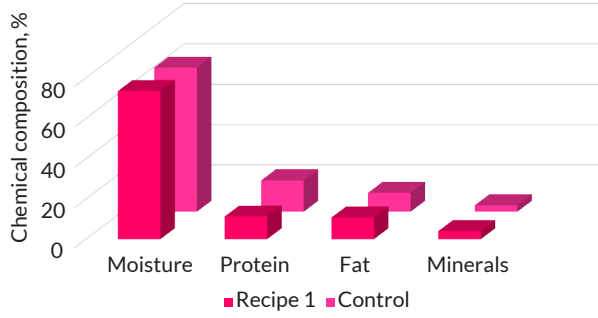

Fig. 15.11 Comparative analysis of the chemical composition of cooked sausage products (Sample 1)

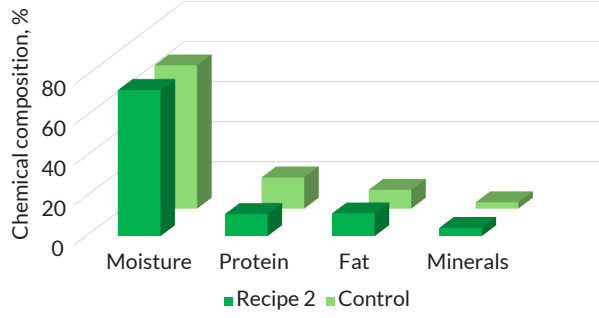

Fig. 15.12 Comparative analysis of the chemical composition of cooked sausage products (Sample 2)

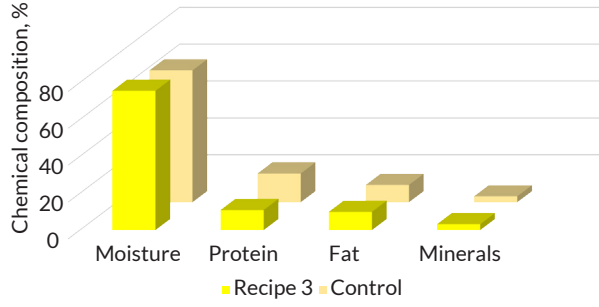

Fig. 15.13 Comparative analysis of the chemical composition of cooked sausage products (Sample 3)

The energy value of the product was calculated according to MU 4287-86. The obtained data are presented in the **Table 15.11**.

Table 15.11 Energy value of cooked sausage products, %

Indicator	Boiled sausage products from non-traditional raw materials			
	Control	Sample 1	Sample 2	Sample 3
Energy value, kcal	148.3 ± 0.54	143.7 ± 0.67	149.5 ± 0.63	134 ± 0.71

Note: $n = 5$, $p \leq 0.05$

An analysis of the obtained data shows that the energy value of the experimental samples is generally comparable to that of the control sample. This similarity is attributed to only minor differences in their chemical composition.

The acid number serves as a key quality indicator reflecting the freshness of fats, as it measures the content of free fatty acids, including those produced through the oxidation of fish fat during storage.

Determining the acid number is one of the primary methods for assessing the quality and freshness of fat, particularly in meat and fish-based products. It reflects the accumulation of free fatty acids (FFA) formed due to lipid hydrolysis caused by tissue or microbial lipases. An increase in the acid number in fish raw materials during storage is a reliable indicator of lipid hydrolytic spoilage [37]. It is established that FFA accumulation indicates not only hydrolysis but may also serve as a secondary marker of fat oxidation, which negatively affects the organoleptic properties of the product [38].

15.7 Research on the fatty acid composition of cooked sausage products

The fatty acid spectrum was determined according to DSTU ISO 5508-2001 [39] by gas chromatography of fatty acid methyl esters. Sample preparation was carried out according to DSTU ISO 5509-2002 [40]. Chromatographic analysis of fatty acids was performed on a Trace Ultra gas chromatograph with a flame ionization detector, on a capillary column SP-2560 (Supelco). The method limit is < 0.01%. The results of the studied samples are presented in **Tables 15.12–15.14**, and the total amount of fatty acids is presented in **Fig. 15.14–15.16**.

The comparative characteristics of the amount of fatty acids of the studied samples are presented in **Table 15.15** and **Fig. 15.17**.

Table 15.12 Fatty acid composition in cooked sausage product (Sample 1)

Fatty acids	Content, g/100 g of fat
Caproic acid (C6:0)	0.11
Capric acid (C10:0)	0.26
Myristic acid (C14:0)	0.42
Pentadecanoic acid (C15:0)	0.11
Palmitic acid (C16:0)	10.00
Palmitoleic acid (C16:1)	1.07
Stearic acid (C18:0)	3.37
Oleic acid (C18:1n9c)	23.93
Linoleic acid (C18:2n6c)	54.19
Arachidic acid (C20:0)	0.13
Cis-11-eicosenoic acid (C20:1n9)	0.56
Linolenic acid (C18:3n3)	0.52
Geneicosanoic acid (C21:0)	0.17
Behenic acid (C22:0)	0.16
Cis-8,11,14-eicosatrienoic acid (C20:3n6)	0.41
Erucic acid (C22:1n9)	0.32
Lignoceric acid (C24:0)	1.58
Cis-4,7,10,13,16,19-docosahexaenoic acid (C22:6n3)	2.69
Σ saturated fatty acids	16.31
Σ unsaturated fatty acids	83.69
Σ monounsaturated fatty acids	25.88
Σ polyunsaturated fatty acids	57.81
ω 6 fatty acids	54.60
ω 3 fatty acids	3.21

Table 15.13 Fatty acid composition in cooked sausage product (Sample 2)

Fatty acids	Content, g/100 g of fat
Caproic acid (C6:0)	0.03
Capric acid (C10:0)	0.05
Undecanoic acid (C11:0)	0.03
Lauric acid (C12:0)	0.09
Myristic acid (C14:0)	0.45
Pentadecanoic acid (C15:0)	0.06
Palmitic acid (C16:0)	10.17
Palmitoleic acid (C16:1)	1.12
Stearic acid (C18:0)	3.52
Oleic acid (C18:1n9c)	27.99
Linoleic acid (C18:2n6c)	48.17
Arachidic acid (C20:0)	0.16
Cis-11-eicosenoic acid (C20:1n9)	0.75
Linolenic acid (C18:3n3)	0.59
Geneicosanoic acid (C21:0)	0.16
Cis-11,14-eicosadienoic acid (C20:2n6)	0.24
Behenic acid (C22:0)	0.23
Cis-8,11,14-eicosatrienoic acid (C20:3n6)	0.36
Cis-11,14,17-eicosatrienoic acid (C20:3n3)	0.33
Lignoceric acid (C24:0)	1.90
Cis-4,7,10,13,16,19-docosahexaenoic acid (C22:6n3)	3.60
Σ saturated fatty acids	16.85
Σ unsaturated fatty acids	83.15
Σ monounsaturated fatty acids	29.86
Σ polyunsaturated fatty acids	53.29
ω 6 fatty acids	48.77
ω 3 fatty acids	4.52

Table 15.14 Fatty acid composition in cooked sausage product (Sample 3)

Fatty acids	Content, g/100 g of fat
Caproic acid (C6:0)	0.04
Caprylic acid (C8:0)	0.04
Capric acid (C10:0)	0.17
Myristic acid (C14:0)	0.42
Pentadecanoic acid (C15:0)	0.07
Palmitic acid (C16:0)	9.23
Palmitoleic acid (C16:1)	1.06
Stearic acid (C18:0)	3.68
Oleic acid (C18:1n9c)	24.16
Linoleic acid (C18:2n6c)	55.75
Arachidic acid (C20:0)	0.13
Cis-11-eicosenoic acid (C20:1n9)	0.41
Linolenic acid (C18:3n3)	0.53
Geneicosanoic acid (C21:0)	0.18
Cis-11,14-eicosadienoic acid (C20:2n6)	0.08
Behenic acid (C22:0)	0.10
Cis-8,11,14-eicosatrienoic acid (C20:3n6)	0.49
Cis-11,14,17-eicosatrienoic acid (C20:3n3)	0.20
Lignoceric acid (C24:0)	1.31
Cis-4,7,10,13,16,19-docosahexaenoic acid (C22:6n3)	1.95
Σ saturated fatty acids	15.37
Σ unsaturated fatty acids	84.63
Σ monounsaturated fatty acids	25.63
Σ polyunsaturated fatty acids	59.00
ω 6 fatty acids	56.32
ω 3 fatty acids	2.68

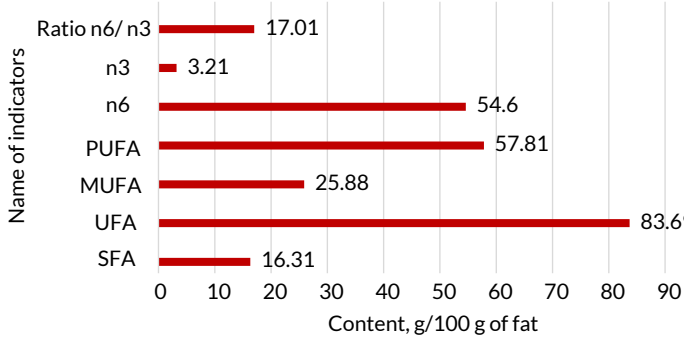

Fig. 15.14 Total fatty acid content in Sample 1

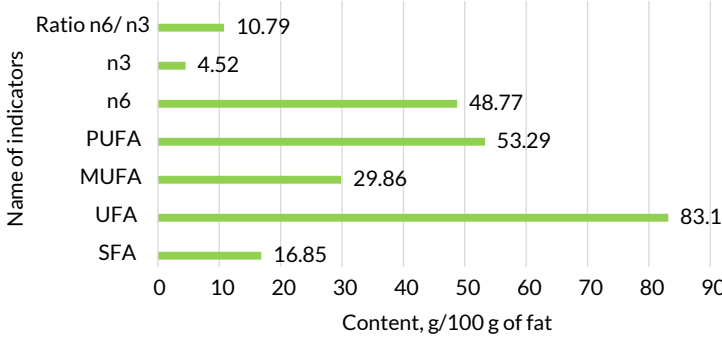

Fig. 15.15 Total fatty acid content in Sample 2

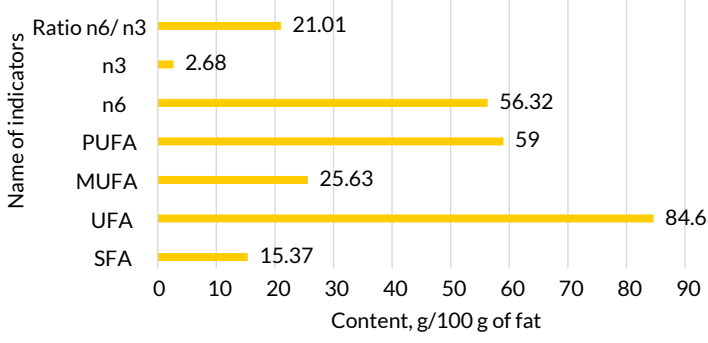

Fig. 15.16 Total fatty acid content in Sample 3

Table 15.15 Comparative characteristics of the amount of fatty acids in the studied samples

Indicator	Sample 1	Sample 2	Sample 3
SFA	16.31	16.85	15.37
UFA	83.69	83.15	84.63
MUFA	25.88	29.86	25.63
PUFA	57.81	53.29	59.00
n6	54.6	48.77	56.32
n3	3.21	4.52	2.68
Ratio n6/ n3	17.01	10.79	21.01

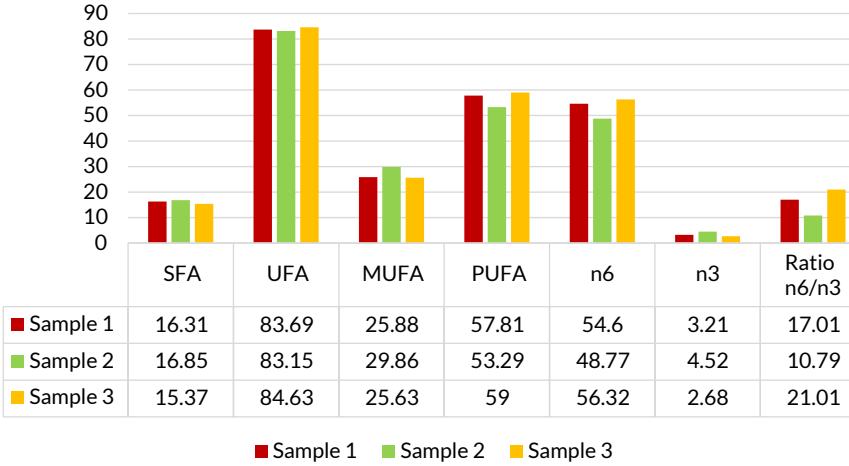

Fig. 15.17 Comparative characteristics of fatty acid content

The total amount of SFA remains almost unchanged. The content of SFA in the obtained samples does not exceed the daily intake. The total amount of UFA does not change significantly in the studied samples. The total amount of MUFA remains almost unchanged. A high indicator is observed in Sample 2. The total amount of PUFA remains almost unchanged. A high indicator is observed in Sample 3. The indicator of the quantity of Omega-6 prevails in Sample 3 over Samples 1 and 2. The indicator of the quantity of Omega-3 prevails in Sample 2. The result obtained in Sample 3 is twice as low as in Samples 1 and 2.

15.8 Dynamics of physicochemical quality indicators of cooked sausage products during storage

The evaluation of organoleptic indicators for cooked sausage products was conducted over 6 days at temperatures ranging from 0°C to 5°C using a five-point scale. The results of changes in organoleptic indicators of cooked sausage products during storage over 6 days are presented in **Fig. 15.18**.

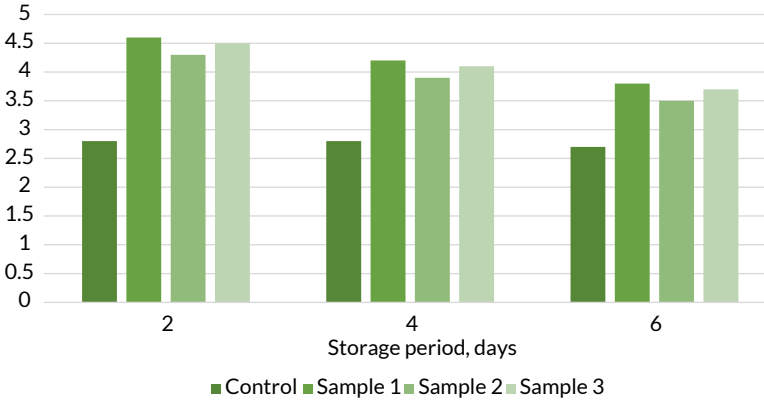

Fig. 15.18 Dynamics of organoleptic evaluation indicators during storage

When conducting an organoleptic assessment, it was found that the most optimal storage period for cooked sausage products is 3 days. During this period, cooked sausage products correspond to high taste properties. When storing cooked sausage products (tested samples) for more than 4 days, a decrease in organoleptic properties (loss of saturated color, appearance of a strong fishy odor, deterioration of taste) is observed due to the absence of a color fixative (sodium nitrite and quality indicators due to deterioration of the muscle tissue of the raw material compared to the control sample.

The physicochemical properties of cooked sausage products were studied over 6 days at temperatures ranging from 0°C to 5°C. The results of changes in moisture content in cooked sausage products over 6 days during storage are presented in **Fig. 15.19**.

From the data presented in **Fig. 15.19**, it can be observed that the moisture content of cooked sausage products decreases during storage. The greatest dynamics of changes in moisture content is observed in Sample 3 due to the high moisture content in the product compared to the control. In Samples 1 and 2, less pronounced dynamics of changes in moisture during storage are observed.

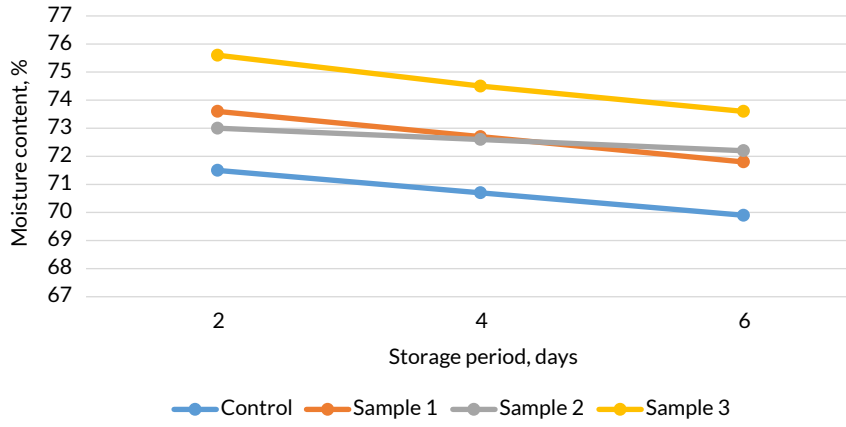

Fig. 15.19 Dynamics of changes in the moisture content of cooked sausage products during storage

Acid value is one of the main quality indicators that characterize the degree of freshness of fat, as it determines the amount of free fatty acids, including those formed during the oxidation of fish fat during its storage.

During storage, free fatty acids accumulate as a result of lipid hydrolysis in muscle tissues, catalyzed by tissue lipases. The extent and direction of this hydrolytic process were assessed based on the buildup of free fatty acids in the lipids of fish muscle tissue. Changes in the acid number of lipids during cold storage of both experimental and control cooked sausage samples are illustrated in **Fig. 15.20**.

The content of peroxide compounds in fat was judged by the value of the peroxide number, which is a reasonably sensitive indicator that characterizes the beginning and depth of oxidative deterioration of fat.

The change in the peroxide number of lipids during the storage of experimental and control samples of cooked sausage products is presented in **Fig. 15.21**.

Measuring the peroxide value enables the early detection of oxidation processes and the formation of spoilage products, well before they can be identified through organoleptic assessment. As illustrated in **Fig. 15.21,** the peroxide value, like the acid value, increases throughout storage, though it remains within acceptable limits by the end of the storage period.

As noted by F. Shahidi and Y. Zhong [33], the early stage of lipid oxidation is a highly sensitive indicator of the initial phases of autoxidation. It is widely used to assess the oxidative stability of food products.

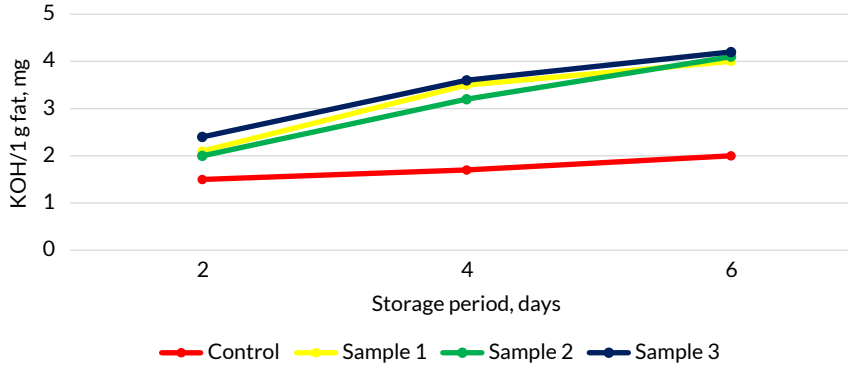

Fig. 15.20 Dynamics of changes in the acid number of cooked sausage products during storage

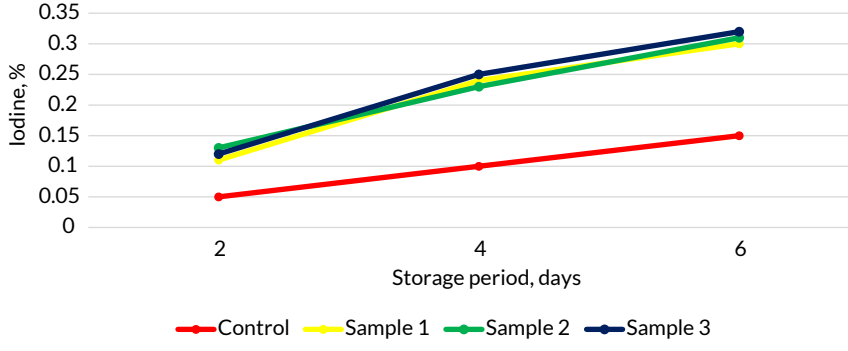

Fig. 15.21 Dynamics of changes in the peroxide value of cooked sausage products during storage

Research by R. Domínguez et al. [31] indicates that the peroxide value is closely related to storage duration, the quality of the lipid raw material, and the presence of antioxidant compounds in the product. A gradual increase in this indicator signals the activation of oxidation processes. In contrast, slower growth in specific samples (such as Sample 3) may result from the inclusion of components with pronounced antioxidant properties or a more stable fatty acid composition.

Determination of peroxide value is one of the key methods for assessing the initial stages of lipid oxidation in meat and fish products. This indicator allows to quickly detect the development of oxidative processes long before the appearance of charac-

teristic changes that can be recorded by organoleptic methods [35–38]. Since peroxide compounds are the primary products of the autocatalytic oxidation of fats, their content directly indicates the stability of the lipid fraction under storage conditions.

The increase in peroxide value during product storage is an expected phenomenon, which confirms the activation of oxidation processes, especially in the presence of unsaturated fatty acids inherent in fish raw materials. However, in cases where natural antioxidants or more stable fat components are used, as in Sample 3, the rate of peroxide accumulation is significantly reduced ($p < 0.05$ compared to control), as confirmed by the Tukey test results. This indicates the effectiveness of functional ingredients that act as oxidation inhibitors [36].

As S. Lee notes, the peroxide value is an extremely sensitive indicator of the initial stages of autooxidation, making its monitoring a reliable tool for predicting the shelf life and quality control of products. In addition, according to R. Domínguez et al., this indicator is closely correlated with the duration of storage, the quality of the fatty raw material and the presence of antioxidant substances. Thus, the gradual increase in the peroxide value in the tested samples, which remains within the regulatory values, confirms the proper technological stability of the product and the effectiveness of the developed formulation [37].

15.9 Microbiological indicators of cooked sausage products

For food safety, cooked sausage products must comply with microbiological control. The regulated compliance indicators are presented in **Table 15.16**.

Table 15.16 Microbiological quality indicators of cooked sausage products

Product group	Number of mesophilic aerobic and facultative anaerobic microorganisms, CFU per 1 g/cm³, not exceeding	Acceptable levels, 1 g/cm³
Control	2.4×10^3	Not more than 1×10^5
Sample 1	1.5×10^3	
Sample 2	0.7×10^3	
Sample 3	0.9×10^3	

According to **Table 15.16**, it can be concluded that the number of mesophilic aerobic and facultative anaerobic microorganisms CFU in 1 g/cm³ should not exceed 2.5×10^3, bacteria of the coliform group – 1.0, S.aureus – 1.0, bacteria of the genus Proteus – 0.1, pathogenic microorganisms, including bacteria (Salmonella), viruses – 25.

Based on the results obtained, it can be concluded that the microbiological indicators of the sausages remained within acceptable limits over a period of four days.

Based on the results of the research and the developed recipe, a new type of boiled sausage was introduced into production under the "Savin Product" trademark. The recipe was adapted to the conditions of industrial production, taking into account modern requirements for quality, nutritional value and product safety.

After the launch of production, the sausage product aroused interest among consumers who prefer more natural and functional meat products. The addition of spelt flour contributed to the enrichment of the sausage with protein, dietary fiber and microelements, which had a positive effect on its perception by buyers. Consumers noted the improved texture, pleasant taste and health benefits. Today, the product demonstrates stable demand and is actively sold through retail chains, which indicates its successful positioning in the market of functional meat products.

15.10 Conclusion

The conducted research confirmed that the incorporation of 10% chicken meat, 6% spelt flour, and selected dried vegetables significantly improved the quality characteristics of cooked fish sausages based on hake. Experimental samples demonstrated an increase in protein content to 16.4–17.2 g/100 g, representing an 8–10% improvement compared to the control (15.1 g/100 g). The moisture-holding capacity increased to 86.3% (in the bell pepper sample), enhancing juiciness and texture. Structural and mechanical tests revealed that the shear force in Samples 2 and 3 increased by 18–20%, indicating an improvement in the density and cohesiveness of the product matrix. During 10 days of refrigerated storage, Sample 3 exhibited the lowest increase in acid value (from 1.7 to 2.3 mg KOH/g fat) and peroxide value (from 1.6 to 2.1% Iodine), suggesting enhanced oxidative stability due to the presence of natural antioxidants.

The results support the initial hypothesis that the proposed formulation has a positive impact on the physicochemical, structural, and sensory properties of cooked fish sausages. These findings suggest the potential for scaling up the developed formulation in pilot-scale production and integrating it into functional food product lines within the fish and meat processing industry.

Nonetheless, the current study is subject to certain limitations, including the lack of extended microbiological stability data and a limited assessment of shelf life under variable temperature conditions. Future work should focus on broader screening of plant-based functional ingredients, long-term storage evaluation, and consumer preference testing to further optimize the formulation and ensure commercial viability.

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