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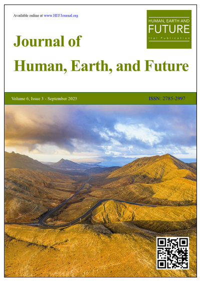

Analysis of Qualitative Characteristics of Barley Milk by Modern Methods

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Abstract

Barley milk is a valuable source of high-quality proteins and balanced nutrients, making it a promising component of dairy and cereal products. Optimisation of its production processes requires comprehensive product characterisation, particularly with regard to the physical stability of proteins. Various analytical methods can be used to evaluate the qualitative characteristics of plant-based drinks. In this study, differential scanning calorimetry (DSC) was used to study the thermodynamic stability and denaturation of proteins, and Fourier transform infrared spectroscopy was used to qualitatively analyse the functional groups that determine the product's structural features. It was found that barley milk has high nutritional value, including significant contents of proteins, saturated fatty acids, dietary fibre, B vitamins and minerals. β-glucan in barley (1.5–8%) helps stabilise the viscosity of the drink, playing a key role in its overall stability. FTIR spectroscopy data confirmed the presence of characteristic peaks of carbohydrates, indicating a high complex sugar content. The DSC results showed that both the initial and peak denaturation temperatures increase with protein concentration. At a low concentration of barley milk (1.5%), one pronounced endothermic peak was observed, whereas at higher concentrations the peaks became clearer and more defined. The data obtained have significant implications for food technology and human health, contributing to the development of more sustainable and functional food products.

Keywords: Barley Milk; Qualitative Indicators; Fourier Transform Infrared Spectroscopy; Differential Scanning Calorimetry; Nutritional Value; Protein Denaturation; β-glucan; Heat Treatment.

1. Introduction

Current trends in nutrition are aimed at the development and implementation of functional products that promote health and prevent nutrition-related diseases. A key task in this area is to meet human physiological needs for energy and essential nutrients. Providing the population with high-quality, biologically complete products has significant social significance, particularly against the background of changes in the modern diet, characterised by insufficient dietary fibre, plant proteins and functional components [1].

In recent decades, the consumption of alternative plant-based products has increased, including plant-based drinks, which are an effective source of protein due to their low calorie content, high digestibility and balanced nutritional composition. Such drinks are becoming popular not only among vegetarians and people with lactose intolerance but also among a broader population who monitor their health and diet. The inclusion of plant components in food

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products makes it possible to enrich them with vitamins, minerals, dietary fibre and other bioactive compounds, making them a promising alternative to dairy products [2, 3].

Among the various cereals used to produce plant-based milks, barley is noted for its unique chemical composition and high functional properties. Barley grain is rich in soluble fibre, particularly β-glucans, which can promote lipid and carbohydrate metabolism, reduce cholesterol and blood sugar levels, and improve intestinal microflora [4]. In addition, barley is a source of plant proteins, necessary for the growth and repair of tissues, and contains B vitamins (niacin, riboflavin, thiamine), as well as minerals such as iron, magnesium, selenium and zinc, which play a key role in maintaining energy metabolism and the functioning of the immune system [5].

Plant-based milk can be produced not only from barley but also from other cereals such as oats, rice and corn, as well as from legumes, including soybeans, peas and chickpeas. For example, oat milk is widely used due to its high concentration of β-glucans with prebiotic properties, as well as its mild taste and texture similar to cow's milk [6]. Rice milk is hypoallergenic and high in complex carbohydrates, making it suitable for people with sensitive digestion [7]. Soy and pea drinks are complete protein sources, containing all essential amino acids, and their health effects and nutritional value are being studied [8, 9].

The bulk of barley carbohydrates is starch, and the content of mono- and oligosaccharides varies from 1.4 to 6.8% depending on the variety and growing conditions [10, 11]. However, the technological features of processing barley in plant-based milk production remain insufficiently studied, particularly in terms of preserving its nutritional value, the stability of the protein–carbohydrate complexes and the organoleptic characteristics (colour, taste, aroma, consistency) of the final product.

The quality characteristics of plant-based milk strongly depend on the food matrix and processing methods, including thermal treatment, homogenisation and mixing with other ingredients. Excessive heating can cause undesirable chemical changes, leading to the destruction of amino acids and vitamins, darkening of the drink and the appearance of extraneous tastes [12, 13]. The effect of heat treatment on the structure of proteins in plant-based milk and their interactions with other components has not been sufficiently studied, making it necessary to further investigate the physicochemical processes occurring during the production and storage of such beverages.

Modern analytic methods should be used for an in-depth study of the structure of proteins and their stability under heat treatment conditions. Differential scanning calorimetry (DSC) is one of the most accurate methods for examining the thermodynamic stability of proteins, including the denaturation temperature, thermal effects and structural changes of protein molecules during processing. This method is widely used in the food industry to evaluate the thermal stability of protein systems and optimise production parameters [14, 15].

Another important tool for protein analysis is Fourier transform infrared (FTIR) spectroscopy, which is used to study the structural changes of molecules under the influence of factors such as thermal and mechanical treatment. This method provides an opportunity to identify functional protein groups, which are important for determining their functional activity and interactions with other components of the food system [16, 17].

Although oat and soy milk have been actively studied in recent years, research on barley milk remains fragmentary, with limited investigation of its physicochemical stability and protein thermodynamics [18, 19]. Recent studies have shown that DSC can effectively identify the temperature limits of protein coagulation in plant matrices and can be used to evaluate the thermal stability of food systems [20]. Additionally, FTIR spectroscopy is a promising method for rapidly analysing the composition of plant-based drinks, including those made from cereals [21]. Studies have also been conducted on the effectiveness of enzymatic treatment in developing functional barley drinks [22].

This study aims to analyse the quality characteristics of barley milk using modern analytical techniques, particularly DSC and FTIR spectroscopy. The results provide a deeper understanding of the physicochemical properties, nutritional value and functional capabilities of barley milk, as well as guidance on optimising its production and storage conditions.

The relevance of this work lies in the need to explore barley milk as a promising functional product using modern analytical methods, which is reflected in this paper's structure. It starts with a description of the materials and methods used, followed by an overview of the results of organoleptic, physicochemical and spectroscopic analyses. These findings are then discussed in the context of current research. The paper concludes with proposals for the development and application of barley milk products.

2. Materials and Methods

2.1. Object of Research

The object of the study was barley milk produced at the Astana branch of the Kazakh Scientific Research Institute of Processing and Food Industry LLP, whose main components included barley (20%) and water (75%). Glucose syrup (3.9%) was used as a sweetener, lecithin (0.38%) served as an emulsifier, xanthan gum (0.40%) served as a stabiliser, and carrageenan (0.32%) was used to improve the texture. Samples of soy milk and walnut milk were taken as control samples for comparison.

The recent theoretical interest in plant-based milk drinks, particularly cereal-based ones, is due to their functionality, low environmental impact and potential to improve the nutritional status of the population. Scientific approaches to their study are developed at the intersection of food chemistry, processing technology and nutrition science. A key area of modern theoretical research is the assessment of the structural stability of plant systems, which determines the textural, rheological and organoleptic properties of drinks, as well as their behaviour during heat treatment and storage. Many studies emphasise the importance of assessing not only the nutritional value but also the bioavailability of components, reflecting a modern functional approach to the development of plant-based drinks as elements of diet therapy and preventative nutrition [23–25]. In this study, we theoretically analyse the relationship between the physicochemical characteristics of barley milk – namely its viscosity, thermal stability, spectral profile and structural stability. This makes it possible to develop scientifically sound technological solutions for developing plant-based drinks.

The barley milk examined in this study was produced through the following stages:

1. Soaking: The grain was kept in water at 25–35 °C in a water module of 1:6–1:10 for 6–8 h. This caused the shell to swell, facilitating grinding and ensuring the formation of small fractions.
2. Germination and grinding: The swollen grains were ground with their shells to form a homogeneous dispersed system with an optimal particle size.
3. Heat-assisted extraction: The ground mixture was heated to no more than 90 °C for 40–60 min. This step was critical for obtaining the desired viscosity and maximising the extraction of nutrients.
4. Enzymatic treatment: The mixture was cooled and amylase was added. As cereals are rich in starch, the addition of amylolytic enzymes helped break it down and impart natural sweetness to the drink without adding sugar.
5. Filtration: Impurities were separated in two stages: coarse filtration followed by fine filtration, which removed particles 40–50 μm in size [26].
6. Homogenisation: Xanthan gum and carrageenan were added to stabilise the system, ensure a uniform texture, inhibit the sedimentation of large particles and prevent separation during storage [27].
7. Enrichment with flavour additives: Glucose syrup was added to improve the drink's organoleptic characteristics and increase its content of biologically active compounds.
8. Bottling: The drink was bottled in sterilised 300 ml containers.

Figure 1 provides a flow chart of the production steps.

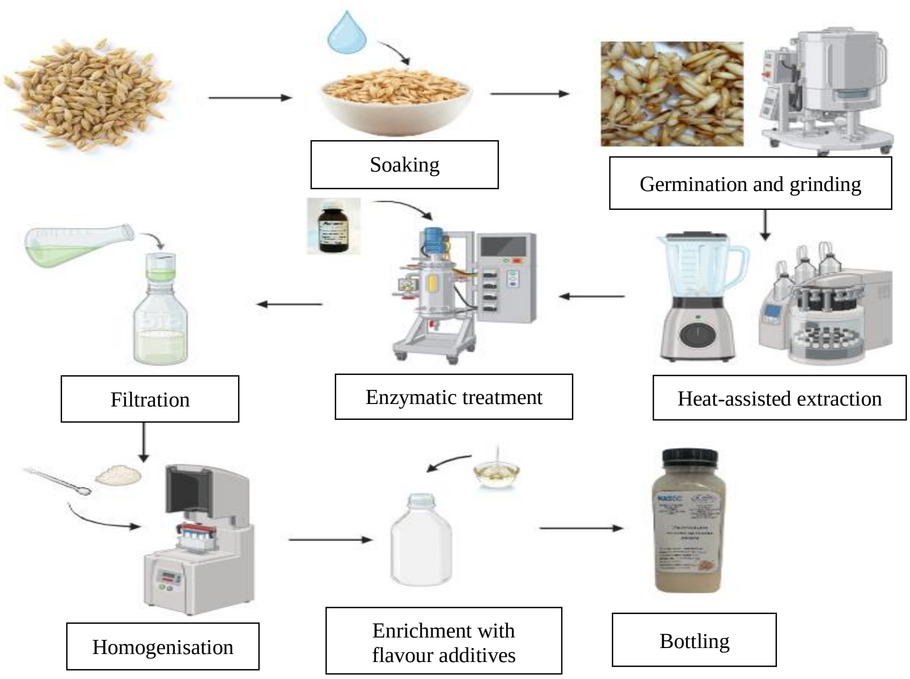

Figure 1. Flow chart for producing barley-based drink

2.2. Analysis Methods

To assess the quality indicators, an organoleptic assessment of the barley milk was conducted using tasting methods in accordance with GOST 6687.5-86 and GOST 8756.11-2015. A modified five-point scale was applied to evaluate the taste characteristics. The descriptive organoleptic scale for the plant milk samples was developed in line with the requirements of GOST 35075-2024 for plant-based drinks. All key analytical methods, including DSC and FTIR spectroscopy, were performed in triplicate. Repeated measurements showed small standard deviations of no more than 2–3%, indicating high reproducibility and reliability. The following methods were used to analyse the physicochemical characteristics.

Moisture content was determined in accordance with GOST 3626-73. Samples were dried in a drying cabinet at 105 °C for 4 h, then cooled in a desiccator and weighed. DSC was used to assess the thermal stability of the protein components in the barley milk, including protein denaturation temperatures and thermal effects arising from structural changes. FTIR spectroscopy was used to analyse protein molecules and their interactions with other components of the drink, enabling the identification of structural changes caused by heat treatment. The stability of the emulsion system was evaluated by measuring the zeta potential and visually assessing the phase separation.

The use of these technological approaches and modern analytical methods has enabled the production of a stable plant-based drink with high nutritional value, homogeneous consistency and balanced taste. Further research aims to optimise the composition of barley milk to enhance its functional properties and increase its shelf life. The moisture content of the milk was determined as follows:

$$\% \text{ Moisture} = \text{Weight loss} / \text{Sample weight} \times 100 \tag{1}$$

The total fat content in the milk was calculated using the Werner–Schmid method. The milk sample was heated with 10 g of concentrated HCl over a Bunsen burner. The mixture was then dried in an oven at 102 ± 2 ºC until a homogeneous mass was obtained. Fat was completely extracted from this residue with warm petroleum ether. The fat content was calculated as

$$\% \text{ Fat} = (W_1 - W_2) \times 100 / W_3 \tag{2}$$

where W_1 is the mass of the flask (g) before fat removal, W_2 is the mass of the flask (g) after fat removal, and W_3 is the mass of the material (g) taken for testing.

FTIR spectroscopy was used to determine the key functional groups present in the samples, assess the colour parameter, and analyse correlations and differences between samples (Figure 2). Interpretation was based on the coincidence principle: the presence and intensity of peaks of the spectrum were compared with reference spectra in the database in the range of 650 to 4,000 cm^{-1} [28].

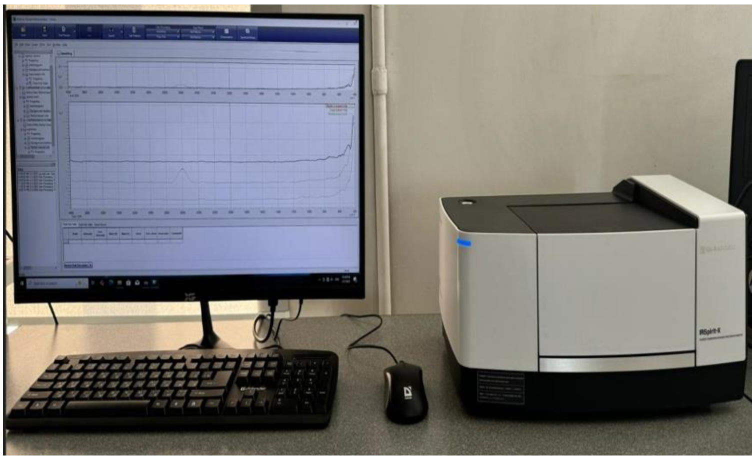

Figure 2. FTIR device (IR Spirit-T, Shimadzu, Japan)

2.3. Determination of Protein Content and Thermal Stability of Protein Structures

The protein content in the barley milk samples was determined using DSC (DSC 1/200 model; Mettler Toledo) (Figure 3), applying a standard nitrogen-to-protein conversion coefficient of 6.25. This method also made it possible to evaluate structural changes in proteins during heat treatment, including the temperature and energy of protein denaturation, which are key parameters in developing and optimising plant-based beverage production.

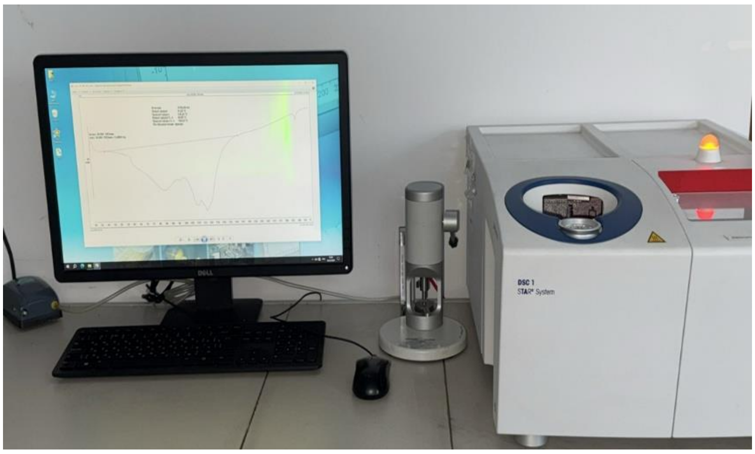

Figure 3. DSC 1/200 differential scanning calorimeter

Before measurement, the barley milk samples were heat-treated in sealed glass tubes placed in a water–oil bath with precise temperature control. Distilled water or polyethylene glycol was used as the heating medium to ensure a uniform temperature distribution and prevent sudden fluctuations. The temperature ranged from 60 to 95 °C, and the heating time ranged from 5 to 120 min. After heating, the tubes were immediately cooled in a water bath at ambient temperature (~25 °C) to preserve the heat-induced changes in protein structures.

For calorimetric analysis, 0.75 g samples of barley milk were hermetically sealed in aluminium DSC capsules, preventing moisture evaporation. An equivalent amount of distilled water was used as a reference in a separate vessel. Measurements were performed at a temperature scanning rate of 1 K/min in a nitrogen atmosphere (pressure 1 bar, flow rate 2 l/h) over a range of 20 to 105 °C.

Analyses were performed in triplicate to ensure reproducibility. Statistical data processing showed low values of standard deviation (no more than 2–3%), indicating the high reliability of the results. From the DSC thermograms, the temperature characteristics (denaturation start temperature T_0 , peak temperature t_m and completion temperature t_e) and denaturation enthalpy (ΔH) were calculated. These data were used to evaluate the effects of heat treatment on the protein component of barley milk, identify critical temperature limits of denaturation, and determine optimal processing conditions for the drink.

3. Results

According to the organoleptic evaluation, the barley plant milk sample was a homogeneous, opaque, cloudy liquid with minor deviations in density and viscosity (Figure 4). Physicochemical parameters, such as pH, density and dry residue, varied depending on the formulation and processing methods, highlighting the significant influence of enzymatic and thermal treatments on the properties of the final product. For example, a decrease in pH and an increase in acidity in the fermented samples indicate the occurrence of lactic acid fermentation, which contributes to greater microbiological stability and a smoother taste.

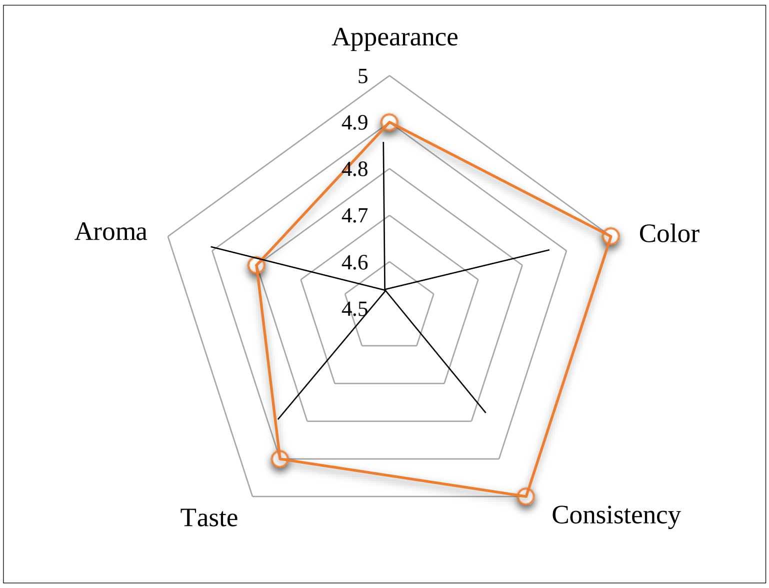

Figure 4. Organoleptic evaluation of barley milk

According to Figure 4, the test sample of barley milk had a uniform consistency and a natural colour ranging from white to light grey, reflecting the pigments naturally present in barley and the effects of processing. The drink had a smooth, viscous consistency typical of this type of plant-based milk.

During storage, the emulsion slightly separated, but the original consistency was restored by shaking, indicating the stability of the system. The presence of a small amount of sediment, as well as suspended particles of natural origin (remnants of grain shells and protein or carbohydrate complexes), did not adversely affect consumer properties or impair the organoleptic perception of the drink. The addition of lecithin as an emulsifier led to a stable emulsion structure, ensuring product uniformity throughout the shelf life.

3.1. Organoleptic Properties

The drink had a mild barley flavour, reflecting its main raw material, although the taste was weak. A slight mealy note was experienced during tasting, but it did not affect the overall perception of the product. Overall, the texture was balanced, with no excessive viscosity or extraneous inclusions that could affect consumer preferences.

The smell and taste of the drink were neutral, without pronounced extraneous notes, indicating the high quality of the raw materials and the suitability of the technological process. The fragrance was subtle but harmoniously combined with the ingredients used, and no foreign odours were detected.

The nutritional value of the experimental sample and the control samples (soy milk and walnut milk) is presented in Table 1. The table shows the content of proteins, fats, carbohydrates, dietary fibre and other biologically active substances, allowing an objective assessment of the nutritional and functional value of the developed product.

This comparative analysis showed differences in the content of key macro- and micronutrients. The experimental sample had lower protein, fat and dietary fibre contents than the control sample but a higher carbohydrate content. These differences are due to changes in the formulation, particularly the introduction of components that affect the nutritional profile of the drink.

Soy milk has a balanced nutritional and vitamin/mineral composition. However, its nutritional density is relatively low; without additional fortification, it cannot be considered a complete functional product [29]. In comparison, barley milk has a lower caloric content (due to its lower fat and protein contents) and also contains valuable trace elements, such as iron, calcium, potassium, magnesium and zinc, although in smaller quantities than soy milk.

Table 1. Nutritional value of barley milk

Nutrients/100 g	Barley milk (experimental sample)	Soy milk (control sample)
Proteins, g	0.6	2.94
Fats, g	0.3	1.99
Carbohydrates, g	8.1	3.05
Dietary fibre, g	0.2	0.4
Vitamin B1, thiamine, mg	0.03	0.1
Vitamin B2, riboflavin, mg	0.04	0.2
Vitamin B3, niacin, mg	0.2	3.3
Vitamin B6, pyridoxine, mg	0.05	1.2
Vitamin E, mg	0.2	2.5
Folate, μg	4	32
Calcium, mg	14	25
Sodium, mg	38	50
Magnesium, mg	10	51
Phosphorus, mg	23	52
Potassium, mg	60	118
Iron, mg	0.3	0.5
Zinc, mg	0.2	0.12
Saturated fatty acids (palmitic acid), g	0.05	0.2
β-glucans, g	0.15	-
Energy, kcal	38	54

In addition, barley milk contains soluble dietary fibre, B vitamins, and macro- and microelements that play an important role in metabolic processes. One of the key components influencing its nutritional value is β-glucans: non-starch polysaccharides with various beneficial properties.

Mixed β-D-glucans of barley endosperm belong to the class of unbranched polysaccharides consisting of 1,4- and 1,3-D-glucopyranose residues in varying proportions. The β-glucan content in barley varies from 1.5 to 8%, and their presence in plant-based milk contributes to the formation of a viscous, stable structure, enabling their use in stabilising food systems. β-glucans have several proven beneficial physiological effects on the human body:

- Anti-inflammatory and antioxidant effects: help reduce oxidative stress and inflammatory processes.
- Immunomodulatory effect: support the activity of macrophages and T-lymphocytes.
- Hypolipidaemic effect: reduce total cholesterol, low-density lipoprotein and triglyceride levels in the blood.
- Hypoglycaemic effect: help reduce blood glucose concentration due to the slow absorption of carbohydrates in the intestine [30].

The introduction of barley into the plant-based milk recipe decreases its energy value, which is particularly important for dietary and functional nutrition. However, the drink is enriched with β-glucans, which are absent in the control samples and can help improve metabolic processes.

The protein component of barley milk includes both soluble and insoluble protein fractions. The key protein groups are:

- Globulins: high-molecular-weight proteins that add structural stability to the product.
- Prolamins and glutelins: proteins that play an important role in texture formation and interaction with other components.
- Albumins: soluble proteins that contribute to the drink's organoleptic characteristics [31].

The protein composition of barley milk includes a high content of essential amino acids, including lysine and tryptophan, which are more abundant than in wheat and corn [32]. This makes barley milk a potentially valuable product for maintaining a balanced diet.

FTIR spectroscopy was conducted to determine the composition of functional groups in the barley milk. The analysis results, presented in Figure 5, revealed characteristic absorption bands corresponding to various classes of compounds, including proteins, carbohydrates and lipids. The FTIR spectra confirmed the presence of β-glucans and allowed determination of the degree of interaction of proteins and other components of the drink, which affects its structural stability. As shown in Figure 5, the use of barley as a base for plant milk not only reduces the product's caloric content but also enriches it with functional components such as β-glucans, dietary fibre and valuable amino acids, making the drink promising for inclusion in a functional nutrition diet.

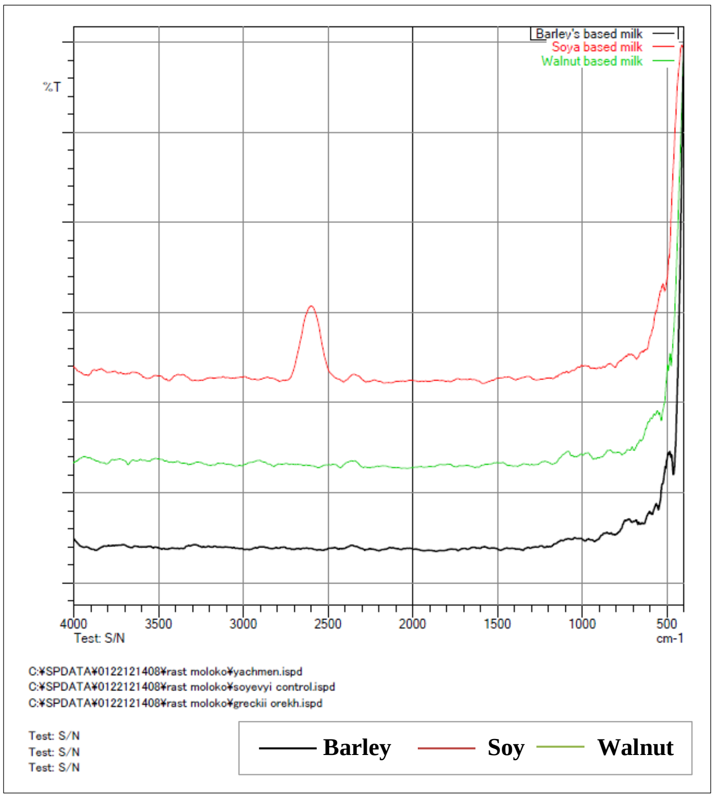

Figure 5. FTIR spectra of samples of plant-based milks

Barley milk, soy milk and walnut milk all showed characteristic absorption bands indicating the presence of water, proteins, lipids and carbohydrates. Analysis of the FTIR spectra revealed key differences in the composition of these samples based on the intensity and location of the absorption peaks.

A sharp increase in transmittance was observed in the range of 500–1,000 cm^{-1}, characteristic of vibrations from complex carbohydrates and phospholipids, confirming these compounds were present in all samples. Soy milk (red line) showed a pronounced peak at 2,600 cm^{-1}, possibly indicating the presence of CO_2 or hydrogen bonds between carbohydrates and proteins. The strong bands at 1,650 cm^{-1} reflected soy milk's significant protein content, consistent with its known composition.

Walnut milk (green line) showed less intense bands in the 2,800–3,000 cm^{-1} range, indicating a lower lipid content compared with soy milk. However, characteristic peaks at 1,000–1,100 cm^{-1} confirmed the presence of nut phospholipids, which help emulsify and structure the product.

Barley milk (black line) exhibited low-intensity peaks at 2,800–3,000 cm^{-1}, indicating lower fat content than the other samples. Strong absorption bands appeared at 1,200–1,400 cm^{-1}, characteristic of carbohydrates and particularly β-glucans, typical of cereals. In the ranges of 1,630–1,650 cm^{-1} and 1,540 cm^{-1}, FTIR spectroscopy revealed:

- The stability of structural elements: bands of amide groups I and II indicate the preservation of secondary structure elements (α-helices and β-sheets).
- Increased peak intensity at 1,040–1,070 cm^{-1}, associated with the accumulation of β-glucans that help stabilise the drink's texture.

Together, these data show that the barley milk has high structural and thermal stability and that the technology effectively preserves its functional and nutritional components.

In summary, FTIR analysis identified key differences between the plant-based milks:

- Soy milk has high protein and lipid contents, as shown by the strong spectral peaks.
- Walnut milk contains a significant amount of phospholipids but is relatively low in saturated fats.
- Barley milk has a high content of complex carbohydrates, particularly β-glucans, making it a promising source of functional food components.

Figure 6 illustrates DSC curves of the barley milk with protein concentrations of 1.5%, 2.4%, 3.8% and 4.8%.

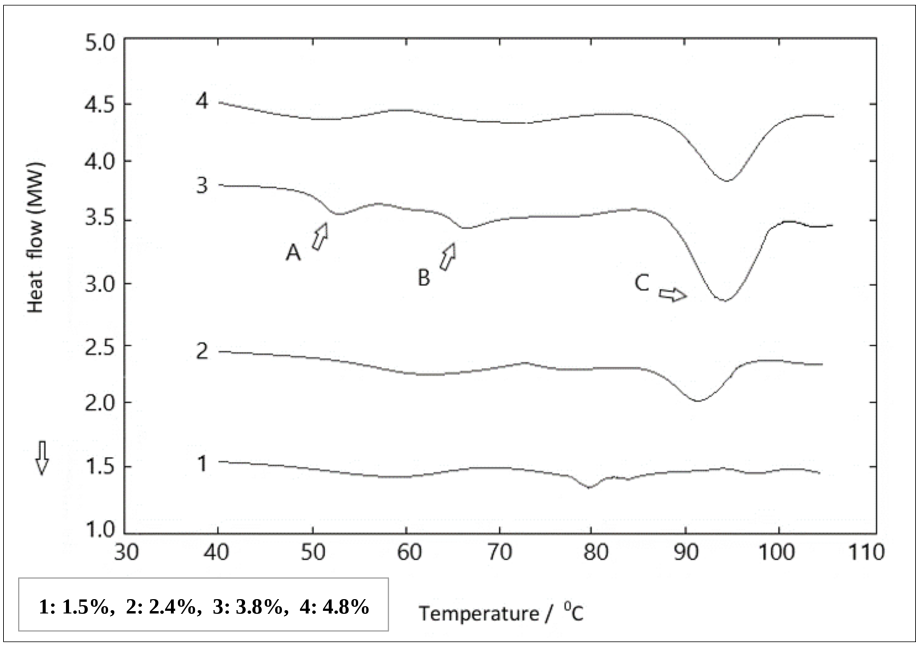

Figure 6. DSC curves of barley milk with different protein concentrations

The DSC analysis showed the following trends:

- The samples with protein contents of 2.4%, 3.8% and 4.8% had three distinct endothermic peaks (A–C), indicating that several protein fractions undergo thermal denaturation at different temperatures.
- The sample with 1.5% protein had only one distinct endothermic peak, suggesting fewer thermally stable protein structures. This may indicate that low-protein samples do not form protein–carbohydrate complexes found in more concentrated samples.

- The initial temperature and peak temperature increased with the protein content, which may be due to increased intermolecular interactions and greater thermal stability of the proteins.
- As the protein concentration increased, the peaks became sharper and more pronounced, indicating increased enthalpy of the endothermic transitions. This suggests denser packing of protein molecules and their interaction with carbohydrate components, including β-glucans.

The thermal analysis confirmed that the protein content significantly affects the thermodynamic properties of barley milk. Increasing protein content improves thermal stability, which may be important in developing thermally stable functional products.

As the denaturation temperature of proteins in plant-based milk depends on their concentration, we selected an optimal sample for further study of thermal treatment. Barley milk with a protein content of 2.4% was used in subsequent experiments, as it had endothermic peaks in the DSC curve, indicating the presence of stable protein–carbohydrate structures.

Figure 7 shows DSC curves of the barley milk after heating at 60, 75, 85 and 95 °C for 5 min. Thermogram analysis revealed the following.

- With increasing temperature, a shift in the endothermic peaks to higher temperatures was observed, indicating gradual protein denaturation and changes in the milk matrix structure.
- At 60 °C, most protein structures remained in their native state, as confirmed by the preservation of characteristic peaks.
- At 75 and 85 °C, active protein denaturation occurred, accompanied by more pronounced thermal effects, indicating intensive structural rearrangements such as protein aggregation and new intermolecular interactions.
- At 95 °C, a marked decrease in peak amplitudes was observed. This may be due to complete protein denaturation, coagulation or association with carbohydrate components (particularly β-glucans), altering the product's physicochemical properties.

The organoleptic evaluations conducted in this study showed that the beverage's textural and taste characteristics depend on the barley concentration and processing conditions. Increasing the protein content to 2.4% enhanced the viscosity and flavour intensity, confirming the role of β-glucans and soluble proteins as structure-forming components. These results are consistent with recent studies on the effect of β-glucans on the consistency and sensory stability of cereal-based beverages [33, 34]. DSC revealed pronounced endothermic peaks at 70–90 °C for the sample with a low protein concentration (1.5%), while sharper and narrower peaks were observed at 2.4%, indicating cooperative denaturation and the formation of stable protein and polysaccharide aggregates. The absence of a thermal peak after processing at 95 °C indicates that protein denaturation and aggregation are complete. While this transformation may reduce the functional properties of proteins, such as foaming and emulsification, it improves digestibility and does not affect nutritional value. These results helped assess the thermal stability of plant milk and identify critical temperatures at which key changes in its composition occur. This information is important for optimising heat treatment to preserve the functional properties of proteins and improve the product's organoleptic characteristics.

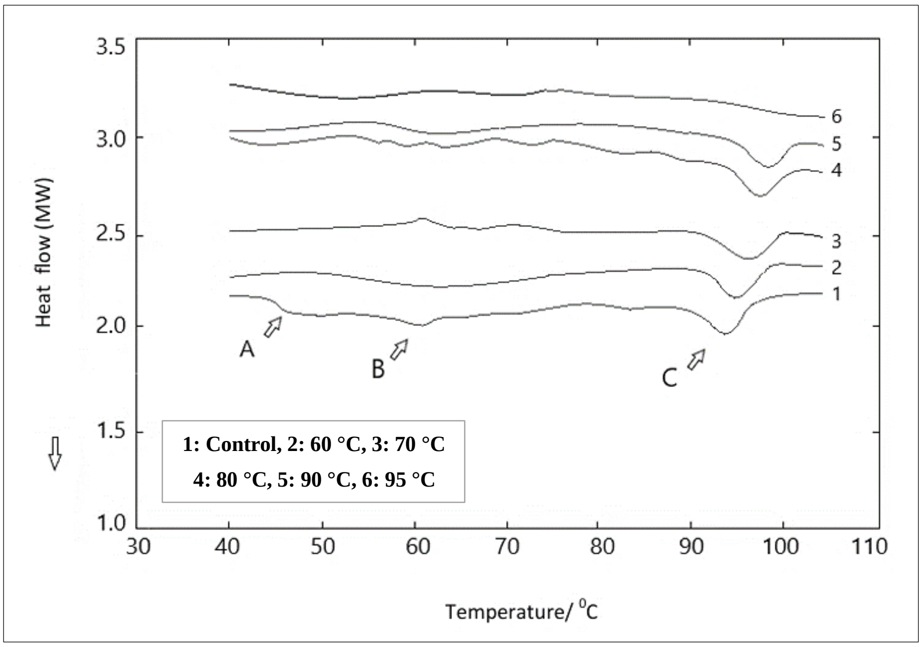

Figure 7. DSC curves of barley milk after heating at different temperatures for 5 min

Analysis of the data presented in Figure 7 revealed patterns in the thermal behaviour of the barley milk during heat treatment. After heating sample 2 at 60 °C for 5 min, peak A disappeared and peaks B and C decreased significantly, indicating that protein fractions with a denaturation temperature of about 60 °C had lost their native structure and undergone irreversible changes. At 70 °C, (sample 3), peaks A and B disappeared, indicating the complete denaturation of most protein components. Thus, the active aggregation of proteins occurred at this temperature, accompanied by the destruction of their tertiary and secondary structures. At higher temperatures, peak C continued to decrease, indicating the gradual destruction of the remaining stable protein structures. At 95 °C (sample 6), all endothermic peaks disappeared, confirming the complete denaturation of the proteins. The absence of characteristic peaks in the DSC curves indicated that no structures capable of phase transitions remained in the system and that an irreversible change had occurred in the drink's protein–carbohydrate matrix.

Thus, DSC revealed that the denaturation temperature is a key parameter in the heat treatment of barley milk, allowing the control of textural properties, the stabilisation of the emulsion and the prevention of undesirable changes such as delamination and excessive thickening. This is particularly important for developing a production process that maintains an optimal temperature regime, preserving the drink's functional and biological properties and ensuring high quality and stability.

4. Discussion

The results of this study confirm that the barley drink has high functional characteristics, consistent with recent findings. As observed by Bozbulut & Sanlier [35], the protein–polysaccharide system showed high stability, attributed to the action of β-glucans as natural stabilisers. Samples with a higher protein concentration demonstrated superior textural and thermal properties, in line with the findings of Cao et al. [36], who reported increased thermal stability of barley milk following ultrasound and β-glucan treatment. The obtained FTIR spectra exhibited absorption bands corresponding to amide groups of proteins, as well as intense signals in the range of 1,040–1,070 cm^{-1}, indicating the presence of β-glucans. These data are comparable to those reported by Kuhnen et al. [37], who used a similar approach to analyse plant matrices based on oats and peas and confirmed the suitability of FTIR spectroscopy for studying structural changes involving fermentation and heat. The DSC analysis revealed a shift in the denaturation temperature with increasing protein concentration and the disappearance of thermal peaks after heat treatment (95 °C, 5 min), suggesting complete coagulation. Similar observations were made by Ahmad et al. [38], who showed that proteins in barley drinks demonstrate significant stability up to a threshold level of thermal stress. This supports the suitability of the product for industrial pasteurisation or ultrahigh-temperature processing. In addition, this study contributes to the evidence base on the use of barley as a raw material for functional drinks. Compared with oats, which have been more widely studied in this context, barley offers not only a similar texture but also a higher β-glucan content, as noted in the review by Edem [39], and supported by experimental data [40]. This makes barley particularly promising for the development of prebiotic drinks and preventative nutrition. Thus, the results of this study not only confirm current scientific findings, but also expand the existing knowledge base by offering a new comprehensive characterisation of a barley drink, including its organoleptic, thermodynamic and functional properties.

The results presented in Table 1 confirm that barley milk is a valuable source of soluble dietary fibre, B vitamins, macro- and microelements, and β-glucans, which play an important role in maintaining metabolic health. Dietary fibre supports digestion, promotes intestinal microbiota and reduces the risk of chronic conditions such as type 2 diabetes and cardiovascular diseases [26, 41].

Analysis of the chemical composition of various plant-based milks indicated their differences in nutrient content and dry matter levels. All plant-based milk analogues have a lower energy value than cow's milk and do not contain lactose, making them suitable for people with lactase deficiency [42]. Soymilk is characterised by a high protein content and low carbohydrate levels [43]; barley milk contains more carbohydrates, mainly in the form of starch; while walnut milk has a high concentration of lipids, including unsaturated fatty acids [31, 44].

Particular attention should be paid to the β-glucans in barley milk. This component has notable antioxidant and immunomodulatory properties, helps reduce blood cholesterol and glucose levels, and can be used as a prebiotic [32, 45-47]. The β-glucan content in barley varies from 1.5 to 8%, making it an important element in functional nutrition.

Organoleptic properties play a key role in consumer perception of food products, including plant-based drinks [34]. The organoleptic evaluation of barley milk samples showed that adding an emulsifier (lecithin) improved stability, prevented delamination and promoted a uniform texture. The grain grinding process did not adversely affect taste or smell, with the product retaining the characteristic properties of the raw material. The absence of foreign odours and tastes indicates the high quality of the raw materials and the suitability of the technological process.

The moisture and fat contents of plant-based milk directly affect its nutritional value and caloric content. In our product, the moisture content was 0.15 g per 100 g and the fat content was 0.3 g, making the drink light, low calorie and suitable for diets aimed at weight control. The fat fraction of barley milk includes saturated and unsaturated fatty acids. In particular, the palmitic acid content was 0.05 g, giving the drink a soft, creamy taste and increasing its gastronomic value. This property makes barley milk a promising ingredient for various culinary products and beverages.

Advanced analytical methods were used to study the composition of barley milk, providing a detailed description of the product. FTIR spectroscopy identified differences between the plant-based milk samples. Characteristic peaks for carbohydrates (β-glucans), proteins and lipids were observed, indicating a high concentration of complex sugars. These data confirm the effectiveness of FTIR spectroscopy for rapid, non-destructive analysis of food products [35, 49]. DSC was used to assess protein denaturation during heat treatment. Most protein fractions were denatured above 70 °C, affecting the structure of the product. The absence of endothermic peaks at 95 °C indicates complete protein denaturation and high thermal stability. Soymilk proteins are less thermally stable and may retain part of their native structure when heated to their critical denaturation temperature [37, 39].

This comprehensive study of barley milk demonstrated its high nutritional value and potential for functional nutrition. Its main findings were as follows:

- The β-glucan content provides biologically active properties that promote health.
- Emulsifiers and stabilisers improve texture and prevent delamination, enhancing consumer appeal.
- FTIR spectroscopy and DSC identified compositional features that can guide further improvements in the production technology.
- Heat treatment affects the protein structure, which must be considered when developing pasteurisation and storage protocols.

Low standard deviations – of up to ±0.02 for pH values and up to ±3% for DSC thermal effects – confirm the high reproducibility of the experiments. The obtained DSC thermograms and FTIR spectra had identical key peaks across all series, indicating the reliability of the methods and the stable composition of the product.

These results are expected to support the development of new formulations of plant-based dairy alternatives with improved functional and organoleptic characteristics.

5. Conclusion

The study examined the organoleptic, physicochemical and spectroscopic characteristics of barley milk. The experimental data confirmed that barley is a promising raw material for producing functional beverages due to its high content of β-glucans, plant proteins, dietary fibre and B vitamins. Optimisation of the process parameters improved the textural and sensory properties of the product, ensuring uniform consistency, stability and a pleasant taste. Advanced analytical methods, such as FTIR spectroscopy and DSC, enabled the detection of changes in the proteins and polysaccharides structures during heat treatment. In particular, the DSC profiles showed a pronounced endothermic peak at a low raw material concentration (1.5%), as well as a clearer denaturation pattern with increased protein component. When the beverage with 2.4% protein was heated to 95 °C for 5 min, the thermal peak disappeared, indicating complete protein denaturation and high thermal stability.

These data were compared with recent studies to highlight the competitive advantages of barley milk over other cereal alternatives. Based on the results, a scientifically substantiated technological scheme for producing a barley beverage was developed, addressing both physiological needs and consumer expectations of quality and taste. The final product has a balanced nutritional composition: 0.6 g of proteins, 0.3 g of fats, 8.1 g of carbohydrates and 0.2 g of dietary fibre per 100 ml. It can be consumed as an independent functional beverage or used as an ingredient in food systems with increased biological value, such as for weight control, vegan diets or lactose intolerance. Its demonstrated benefits include improved metabolism, normalisation of cholesterol levels, digestive support and a general strengthening effect.

The use of modern analytical approaches ensured accurate assessment of the product's stability and quality. A future direction for this research is to analyse the effect of various technological processes, enzymatic treatment and enrichment with probiotic or mineral supplements. The scientific and practical results obtained can support the development of new cereal-based drinks with functional nutrition aimed at enhancing health and improving the quality of life.

In summary, this study confirmed the technological and functional viability of barley milk as a product with high nutritional and biological value. The findings can guide future optimisation of processing modes, raw material selection and the development of specialised or preventative nutrition products.

5.1. Limitations and Future Study

This study has several limitations. It was conducted in a laboratory setting with a small number of samples, which may affect the generalisability of the results. In addition, the effects of storage and pasteurisation conditions on the stability and properties of the barley milk were not considered. Future research should include a wider range of samples and explore industrial production conditions. Another promising direction will be to study the interaction of β-glucans with other components of the drink and assess their effect on the product's functional properties.

6. Declarations

6.1. Author Contributions

Conceptualisation, N.A.; methodology, A.K.; software, M.Y. and A.I.; validation, N.A.; formal analysis, A.I., I.A., and A.D.; investigation, M.S., I.A., and M.S.; resources, M.Y. and A.I.; data curation, M.Y., A.D., and I.A.; writing—original draft preparation, N.A. and I.A.; writing—review and editing, N.A. and M.S.; visualisation, M.S. and I.A.; supervision, A.D. and M.S.; project administration, N.A.; funding acquisition, A.K. and N.A. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

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6.5. Institutional Review Board Statement

Not applicable.

6.6. Informed Consent Statement

Not applicable.

6.7. Declaration of Competing Interest

The authors declare that there are no conflicts of interest concerning the publication of this manuscript. Furthermore, all ethical considerations, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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