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Article

Comparative Characterization of Foaming and Emulsifying Properties of Fruit and Vegetable Additives

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Abstract: This study presents a comparative characterization of foaming and emulsifying properties of fruit and vegetable juices and purees as plant-based additives for food products. The research demonstrates that juices possess significant foaming capacity, whereas purees prepared from the same raw materials exhibit negligible foaming properties. Conversely, vegetable purees demonstrate substantially stronger emulsifying characteristics compared to juices. The superior foaming and emulsifying capabilities of beetroot additives are attributed to the presence of saponins in their composition. Comparative analysis of surface-active properties reveals significant differences among various plant-based additives, with beetroot showing the highest foam formation capacity (285±22%) and foam stability (56±4%), while carrot juice exhibited the lowest surface tension (45.3±1.2 mN/m). These findings provide valuable insights for developing functional food products with enhanced structural and textural properties using natural plant-based emulsifiers and foaming agents.

Keywords: emulsifier, foaming agent, surface-active substances, saponins, surface tension, adsorption layer, medium acidity, relative viscosity, emulsifying capacity

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1. Introduction

Food products with foam and emulsion structures continue to maintain their popularity and diversity in today's food market. The stabilization and preservation of structure during the storage period of such products remains a pressing issue, attracting the attention of scientists and manufacturers alike. Foaming agents and emulsifiers significantly influence the structure and stability of foam and emulsion food products. These substances play a crucial role in stabilizing disperse systems by reducing interfacial tension at the boundary between immiscible phases [1].

Foaming and emulsifying agents form a protective layer around dispersed phase particles, preventing aggregation—the process by which particles enlarge and coalesce. This mechanism preserves the structure and quality of the product. The growing demand for natural, clean-label ingredients has intensified research into plant-based alternatives to synthetic emulsifiers and stabilizers [2].

From a scientific perspective, the foaming and emulsifying properties of plant additives used

in food technology are primarily attributed to the presence of surface-active substances (SAS) such as proteins and pectin compounds in their composition. Additionally, literature analysis reveals that plant raw materials contain triterpene and steroid glycosides—saponins—which exhibit high surface activity [2]. Despite the recognized importance of these compounds, comprehensive comparative studies examining the interplay between chemical composition and functional properties of different plant-based additives remain limited.

The objective of this research was to conduct a comparative characterization of the foaming and emulsifying properties of fruit and vegetable additives, specifically examining the role of saponins in these functional properties. Plant additives were selected based on similarity in technological properties and chemical composition, but differing in the presence or absence of saponins. Beetroot, containing saponins, and apple and carrot, which lack saponins, were chosen as model systems representing these criteria. This comparative approach enables the isolation of saponin effects from other compositional factors.

2. Materials and Methods

Raw Materials. Fresh beetroot (Beta vulgaris), apple (Malus domestica), and carrot (Daucus carota) were procured from local markets in Bukhara, Uzbekistan. The selection criteria included maturity, absence of visible defects, and uniform size. All raw materials were washed, peeled, and processed within 24 hours of procurement to minimize enzymatic degradation and maintain compositional integrity.

Preparation of Juices and Purees. Fruit and vegetable juices and purees were prepared using conventional methods. Cleaned and crushed raw materials were processed in an SVA-1 juice extractor to obtain juices. For puree preparation, cleaned fruits and vegetables were steamed until soft, then homogenized using an MIVP device. All samples were processed at controlled conditions and stored at 4°C until analysis, with all measurements conducted within 48 hours of preparation.

Chemical Composition Analysis. The chemical composition of fruit and vegetable juices and purees was determined using standard analytical methods [3, 4]. Dry matter content was measured gravimetrically by drying samples to constant weight at 105°C. Sugar content was determined by the Luff-Schoorl method. Nitrogen content was assessed by the Kjeldahl method, with protein calculated using a conversion factor of 6.25. Pectin content was determined by the calcium-pectate method. Protopectin, hemicellulose, and cellulose contents were measured using sequential extraction procedures. Saponin content was quantified spectrophotometrically after extraction. Mineral content was determined by ash analysis at 550°C. All determinations were performed in triplicate.

Physicochemical Characterization. Active acidity (pH) was measured potentiometrically using a pH-340 instrument calibrated with standard buffer solutions. Dynamic viscosity of juices was determined using a VPJ-2 capillary viscometer at 20±0.5°C. Surface tension was measured by the maximum bubble pressure method [5]. The strength of the interfacial adsorption layer (IAL) was evaluated using an accepted method based on determining the boundary shear force, involving measurement of torsional force on a disk suspended on a taut thread at the phase boundary [6].

Foaming Properties. The foaming properties of juices and purees were evaluated through foam formation capacity and foam stability [7]. Samples (50 ml) at 20±0.5°C were placed in 250 ml graduated cylinders and whipped using a Tig-2 laboratory mixer at 400 rpm for 6 minutes. Foam formation degree was calculated as the percentage increase in volume immediately after whipping. Foam stability was determined as the percentage of foam volume remaining after 30 minutes of standing at room temperature.

Emulsifying Properties. Emulsions were prepared by adding vegetable oil to juices or purees at a 1:1 ratio (v/v) at 20±0.5°C, followed by mixing with a Tig-2 laboratory mixer at 400 rpm for 6 minutes. Emulsification efficiency was characterized by emulsion stability both in static conditions

and during centrifugation [8]. Emulsifying capacity was calculated as the percentage of emulsified phase relative to total volume. Emulsion stability was determined by centrifugation at 3000 rpm for 15 minutes, measuring the volume of separated phases.

Statistical Analysis. All experiments were conducted in triplicate, and results are expressed as mean ± standard deviation. Statistical analysis was performed using appropriate methods to ensure data reliability and reproducibility.

3. Results and Discussion

Chemical Composition

The chemical composition of fruit and vegetable juices and purees is presented in Table 1. The data indicate that the chemical composition of fruit and vegetable juices and purees is qualitatively similar, differing primarily in the quantitative content of individual components.

Table 1. Chemical composition of fruit and vegetable juices and purees (g per 100 g product)

Component	Beetroot		Apple		Carrot	
	Juice	Puree	Juice	Puree	Juice	Puree
Dry matter	9.8±0.31	13.1±0.63	10.6±0.27	12.7±0.45	8.6±0.25	10.8±0.35
Sugars	7.81±0.16	6.35±0.14	8.78±0.13	7.92±0.12	6.35±0.12	4.84±0.11
Nitrogenous substances	0.32±0.07	0.98±0.06	0.36±0.06	0.59±0.07	0.46±0.07	0.92±0.08
Pectin	0.38±0.04	0.82±0.05	0.27±0.04	0.62±0.08	0.26±0.04	0.68±0.07
Protopectin	-	0.97±0.03	-	0.48±0.04	-	0.74±0.03
Hemicellulose	-	0.84±0.03	-	0.39±0.03	-	0.48±0.02
Cellulose	-	1.24±0.02	-	0.67±0.03	-	1.03±0.04
Saponins	0.07±0.01	0.06±0.01	-	-	-	-
Minerals	0.84±0.02	0.98±0.04	0.53±0.03	0.78±0.03	0.74±0.03	0.87±0.03

All purees exhibited higher dry matter and mineral content compared to juices. Purees contained lower nitrogen compound content than juices. Pectin content in purees was significantly higher than in juices, attributable to the preparation method involving hydrothermal treatment, during which protopectin partially converts to pectin, increasing its total content in the product. Beetroot puree and juice contained nearly equivalent amounts of saponins. Protopectin, hemicellulose, and cellulose were detected only in purees. Beetroot puree exceeded apple and carrot purees in protopectin, hemicellulose, and cellulose content.

Foaming and Emulsifying Properties

Data characterizing the foaming and emulsifying properties of the selected fruit and vegetable juices and purees are presented in Table 2.

Table 2. Foaming and emulsifying properties of fruit and vegetable juices and purees

Property	Beetroot		Apple		Carrot	
	Juice	Puree	Juice	Puree	Juice	Puree
Medium acidity (pH)	6.67±0.03	5.93±0.04	6.58±0.04	5.74±0.03	6.32±0.05	5.63±0.04
Surface tension, mN/m	69.4±1.3	-	56.2±1.4	-	45.3±1.2	-
Relative viscosity	1.82±0.15	-	1.51±0.13	-	1.46±0.12	-
IAL strength at air interface, N/m	0.14±0.01	-	0.11±0.01	-	0.08±0.01	-
IAL strength at oil interface, N/m	0.64±0.03	-	0.52±0.03	-	0.48±0.02	-

Foaming degree, %	285±22	-	185±21	-	145±20	-
Foam stability, %	56±4	-	38±3	-	32±3	-
Emulsifying capacity, %	65±3	78±5	42±3	48±4	49±3	58±4
Emulsion stability, %	78±5	83±4	62±5	67±4	69±5	76±4

The active acidity of fruit and vegetable juices was higher than their corresponding purees. Carrot juice exhibited the lowest surface tension value, while beetroot juice showed the highest. The difference between the minimum value in carrot juice and the maximum value in beetroot juice was substantial at 24.1 mN/m. Among the studied juices, there was no significant difference in relative viscosity values.

The presence of finely dispersed solid phase particles containing large amounts of soluble pectin and insoluble carbohydrates in fruit and vegetable purees determines their consistency and higher structural-mechanical properties compared to juices. The relatively high content of solid tissue particles in purees resulted in poor foaming properties.

Regarding foaming degree and foam stability, the studied vegetable juices ranked as follows in descending order: beetroot juice, apple juice, and carrot juice. Beetroot additives demonstrated superior emulsifying capacity and emulsion stability. The superiority of carrot additives over apple additives is explained by higher content of proteins, soluble pectin, and insoluble carbohydrates.

The strength of the interfacial adsorption layer (IAL) at the oil interface was significantly higher than at the air interface for fruit and vegetable juices, averaging approximately 5-fold. Carrot juice formed the weakest layer at both air and oil interfaces, while beetroot juice created the strongest layer at both types of interfaces. The IAL strength values at the air interface correlated with the foaming degree and foam stability of the juices. The IAL strength values at the oil interface were associated with their emulsifying capacity and emulsion stability.

Discussion

The comparative analysis reveals distinct functional properties among different plant-based additives, particularly regarding their foaming and emulsifying capabilities. The superior performance of beetroot additives can be primarily attributed to the presence of saponins, which are absent in apple and carrot samples. Saponins are naturally occurring glycosides that exhibit strong surface-active properties, effectively reducing interfacial tension and stabilizing both foam and emulsion systems [2].

The observed difference in foaming properties between juices and purees prepared from the same raw materials merits particular attention. While juices demonstrated significant foaming capacity, purees exhibited negligible foam formation. This phenomenon can be explained by their structural-mechanical characteristics, as the surface-active substance (SAS) content remains essentially equivalent. The presence of finely dispersed solid particles, insoluble carbohydrates, and higher viscosity in purees appears to inhibit air incorporation and foam stabilization mechanisms.

Interestingly, the emulsifying properties showed an inverse trend, with vegetable purees demonstrating substantially stronger emulsifying characteristics compared to juices. This finding suggests that the solid phase particles and higher pectin content in purees contribute positively to emulsion stabilization through mechanical barrier effects and enhanced viscosity. The structural-mechanical factor of stability indicates that merely reducing surface tension is insufficient for forming stable foams and emulsions; the formation of a strong interfacial adsorption layer is equally critical [1].

The correlation between IAL strength and functional properties provides mechanistic insight. At the air interface, stronger IAL values corresponded to enhanced foaming degree and stability, while at the oil interface, they related to improved emulsifying capacity and stability. This dual-interface behavior underscores the complexity of surface-active mechanisms in food systems and

highlights the importance of selecting appropriate additives based on desired product characteristics.

The relatively lower organoleptic properties of beetroot juice and purees present a practical challenge for their application as additives in food technology. Future research should focus on developing strategies to mitigate these limitations, potentially through combination with other plant materials, processing modifications, or flavor masking techniques. Nevertheless, the exceptional functional properties of beetroot additives, particularly their saponin-mediated surface activity, present valuable opportunities for developing novel food products with enhanced structural stability.

4. Conclusion

This comparative study of foaming and emulsifying properties of fruit and vegetable additives—beetroot, apple, and carrot juices and purees—reveals several important findings for food technology applications:

Juices possess significant foaming capacity, whereas purees prepared from the same raw materials demonstrate negligible foaming properties. This distinction appears to be governed by structural-mechanical characteristics rather than surface-active substance content, which remains essentially equivalent between juices and purees from identical raw materials.

Conversely, vegetable purees exhibit substantially stronger emulsifying characteristics compared to juices, suggesting that solid phase particles and higher pectin content contribute positively to emulsion stabilization.

Beetroot additives demonstrate superior foaming and emulsifying capabilities, which can be attributed to the presence of saponins in their composition. This finding establishes beetroot as a promising natural functional ingredient for food technology applications.

The research demonstrates that interfacial adsorption layer strength serves as a reliable predictor of functional properties, with correlations observed between air interface strength and foaming characteristics, and oil interface strength and emulsifying properties. However, the practical application of beetroot as an additive requires addressing its relatively lower organoleptic properties through appropriate technological solutions.

These findings contribute to the scientific understanding of plant-based functional ingredients and provide practical guidance for developing food products with enhanced structural stability using natural additives.

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